Dark matter

Candidates and ways of detecting them

(review with a view)

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IVth NExT PhD workshop, The road ahead

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INNOVATIVE ECONOMY NATIONAL COHESION STRATEGY

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Outline

- ✧ Introduction – DM: evidence and general properties
- ✧ Theory frameworks for DM candidates
- ✧ Axion - briefly
- ✧ SUSY neutralino as DM
- ✧ Implications of m_h~126 GeV
- ✧ Implications of direct limits on SUSY
- ✧ Prospects for direct detection
- ✧ Prospects for the LHC
- ✧ Indirect detection
- ✧ Some other recent developments and claims
- ✧ Summary

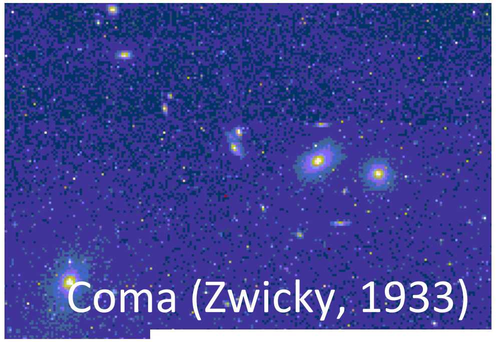
There is more out there than meets the eye

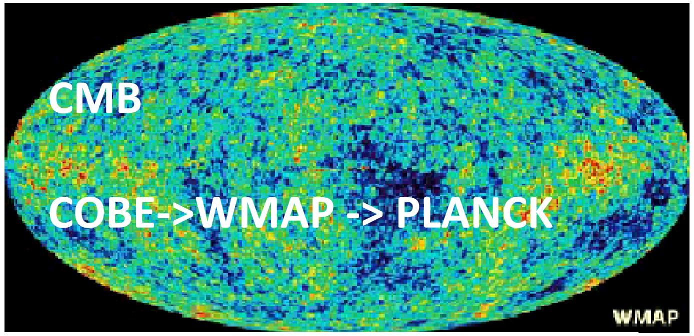
The WIMP Reigns

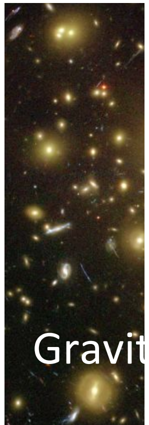
…but remains elusive

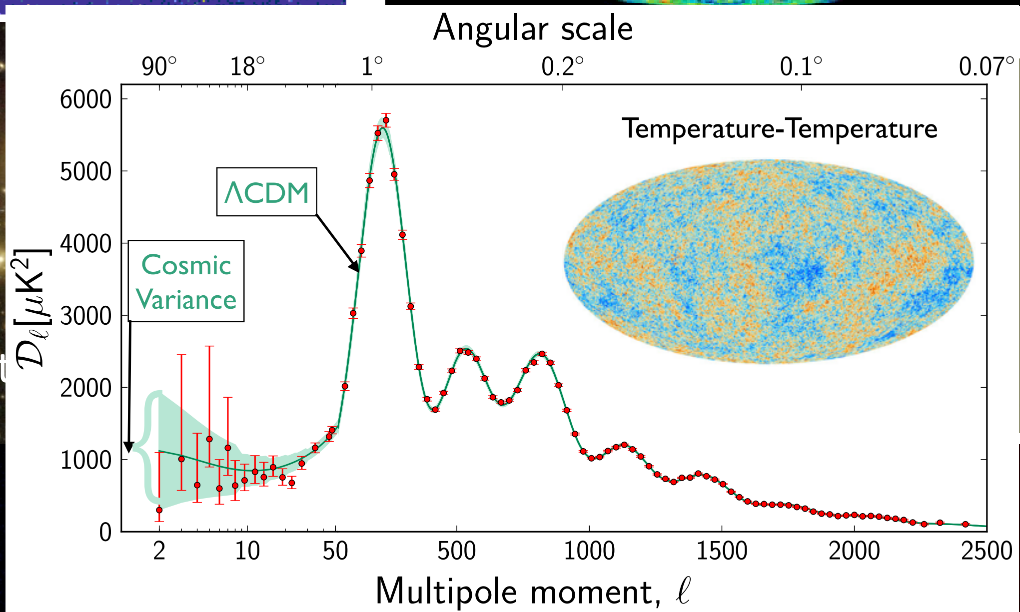
Footprints of Dark Matter

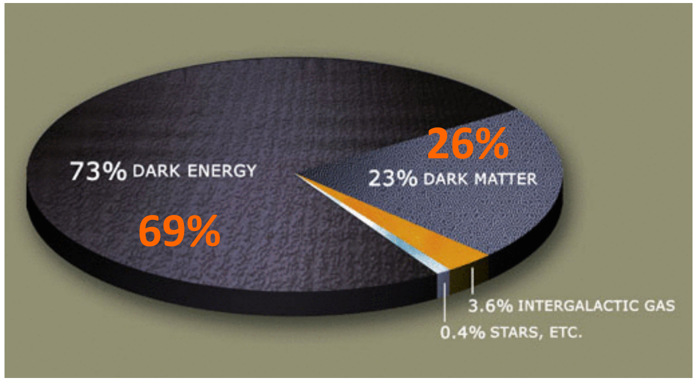
...felt but not seen

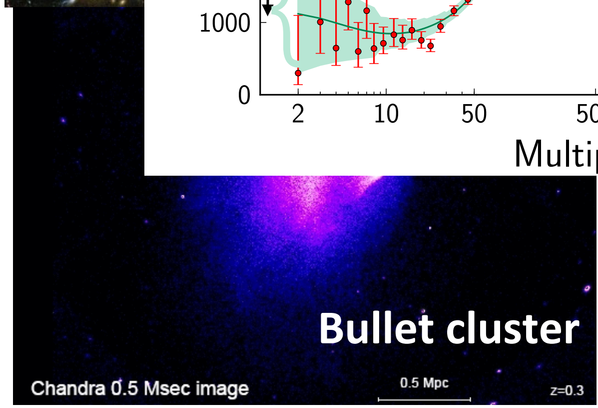


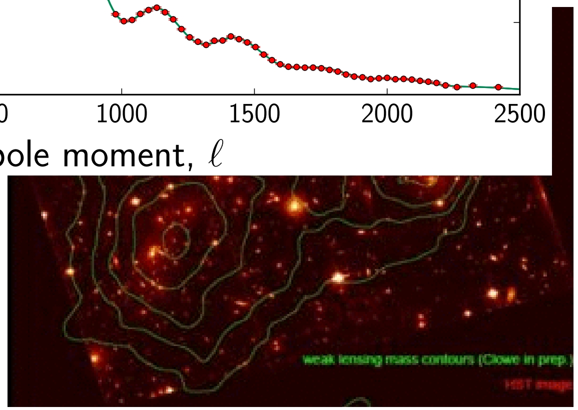


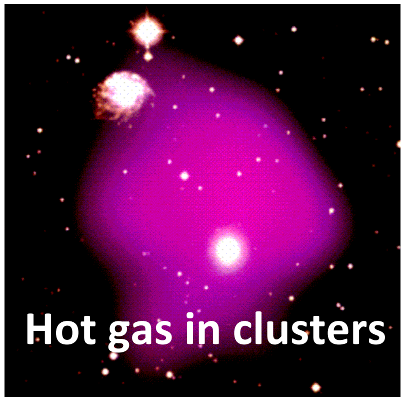












What is the DM?

- non–baryonic
- cold (CDM)

  or possibly (?) warmish

- no electric nor (preferably) color interactions
- relic from the Big Bang
- element of some sensible particle theory

plausible choice ⇒ WIMP

(weakly interacting massive particle)

...a very broad class, not a single candidate

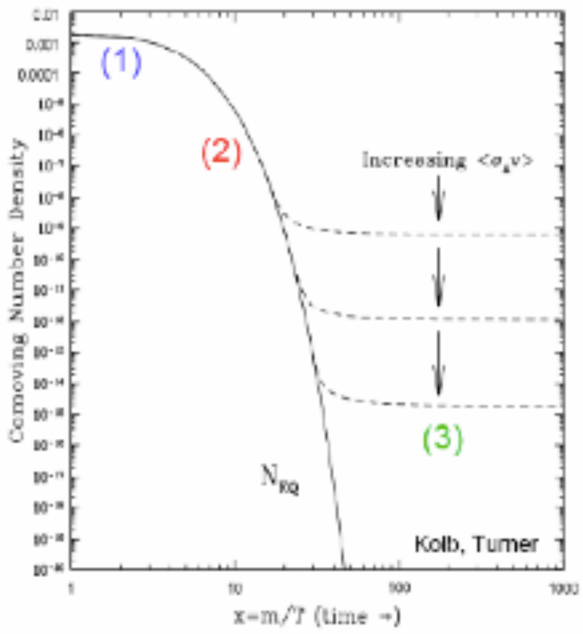
...How weak can weak be?

WIMP: most likely an unknown particle

A simple, persuasive argument:

- WIMPs decouple from thermal equilibrium
- freeze–out when $\Gamma \lesssim H$

WIMP relic abundance



$$\Omega h^2 \simeq \frac{1}{\left\langle \left(\frac{\sigma_{\rm ann}}{10^{-38}{\rm cm}^2}\right)\left(\frac{v/c}{0.1}\right)\right\rangle}$$

$\sigma_{\rm ann}$ – c.s. for WIMP pair–annihilation in the early Universe

v – their relative velocity, $\langle \ldots \rangle$– thermal average

$$\sigma_{\rm ann} \sim \sigma_{\rm weak} \sim 10^{-38}\,{\rm cm}^2 = 10^{-2}\,{\rm pb} \;\Rightarrow\; \Omega h^2 \sim 1$$

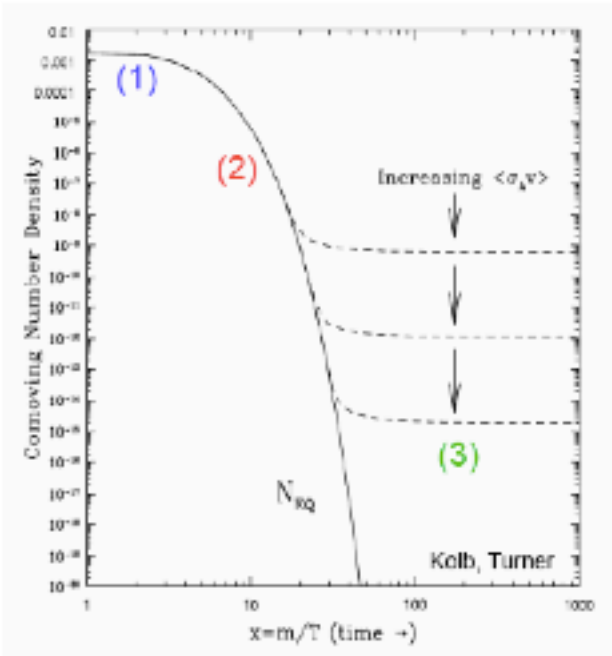
A hint? Possibly, but...

Not "WIMP Miracle" but weak int. – relic density coincidence

Thermal or non-thermal relic?

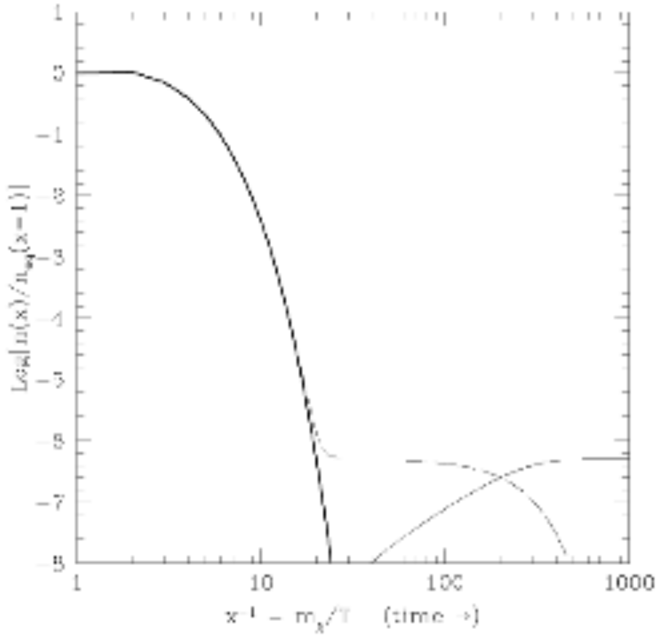
thermal

freeze-out



non-thermal

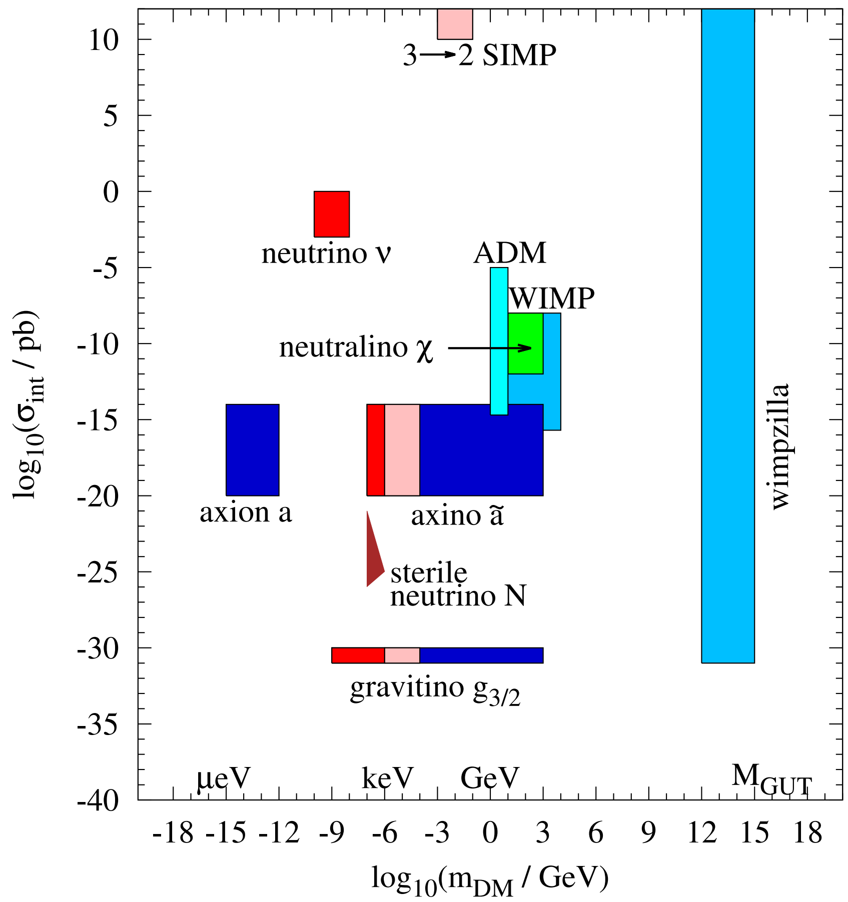
out-of-equilibrium, several mechanisms



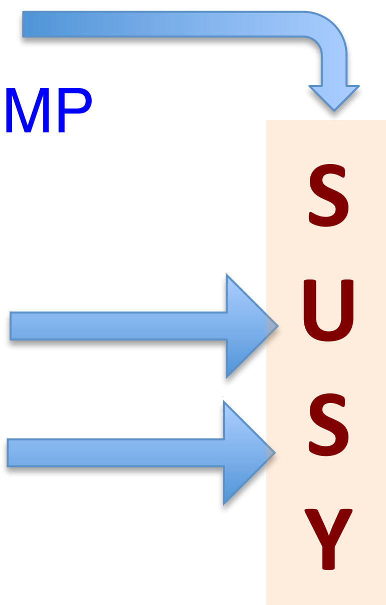
- thermal production (TP): robust
- non-thermal production (NTP): more model-/mechanism- dependent, can be dominant, opens up new possibilities

Well-motivated candidates for dark matter

1307.3330



- neutrino ν – hot DM
- neutralino χ
- "generic" WIMP
- axion a
- axino $\widetilde{a}$
- gravitino $\widetilde{G}$



- vast ranges of interactions and masses
- different production mechanisms in the early Universe (thermal, non-thermal)
- need to go beyond the Standard Model
- WIMP candidates testable at present/near future
- axino, gravitino EWIMPs/superWIMPs not directly testable, but some hints from LHC

Sorting out the dark side…

- **Thermal relics:**

  Produced via processes in thermal equilibrium (e.g., freeze-out)

  - Hot: neutrinos, eV gravitinos, …
  - Warm: sterile neutrinos, keV gravitinos or axinos, …
  - Cold: neutralinos, LKKP, GeV-TeV mass WIMP…, GeV gravitinos or axinos, …

- **Non-thermal relics:**

  Produced via processes outside of thermal equilibrium
  (e.g., from decays of out-of-equilibrium particles)

  - Cold: axions
  - Cold/warm: neutralinos, gravitinos, axinos, …
  - axionic BEC, axion clusters, …
  - solitons (Q-balls, …)
  - wimpzillas, …

- **More than one?…**
  - type of DM species, (e.g., axion & axino, or axion and neutralino, …)
  - type of the same relic: TH and NTH (e.g., two populations (warm & cold)…

Where is the WIMP?

- ➢ **Mass range: at least 20 orders of magnitude**
- ➢ **Interaction range: some 32 orders of magnitude**

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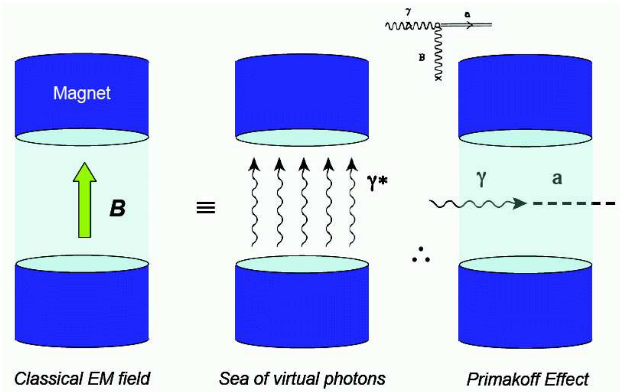
CDM: some theory frameworks

- ✧ **SUSY** <- by far most popular (and best motivated)
- ✧ **Axions from PQ symmetry** <- very strongly motivated
- ✧ **DM and various extensions of the SM (portals/ hidden valleys, extra dim's, strings, …)**
- ✧ **Ad hoc DM models**
- ✧ **Asymmetric DM**
- ✧ **Self-interacting DM**
- ✧ **…**

…most creative activity in the field at present?

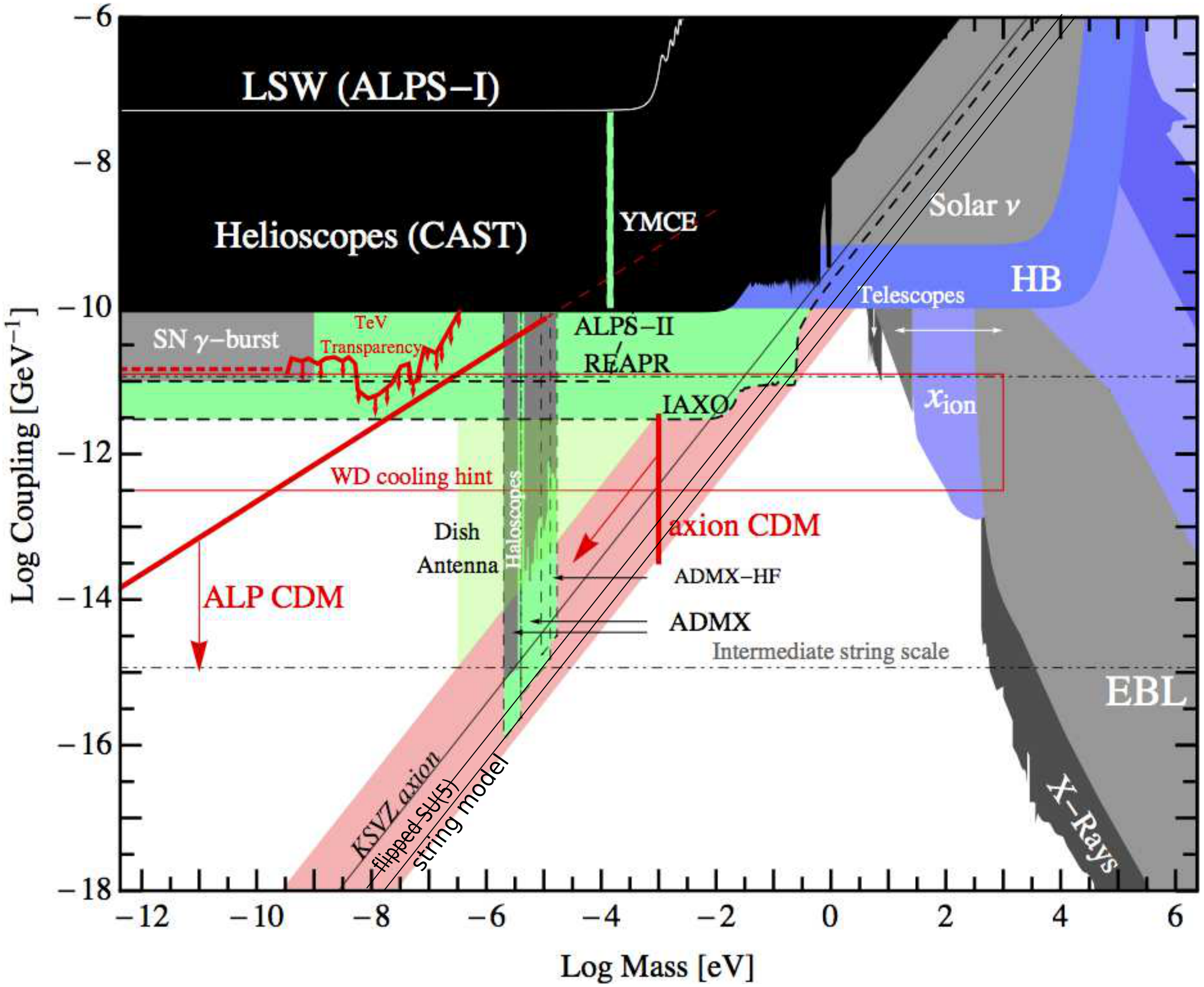
Axions

- a – pseudo-goldstone boson
  by–product of PQ solution of strong CP problem
- global $U(1)$ group spontaneously broken at scale $f_a \sim 10^{11}\,\mathrm{GeV}$
- two main frameworks:
  - DFSZ axion: add two doublets
  - KSVZ axion: add heavy single quark with mass $m_Q \sim f_a$
- $\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$
- $m_a \simeq 10^{-5}\,\mathrm{eV} \;\Leftrightarrow\; \Omega_a \simeq 1$
- DM axion search: resonant cavity
  $a\gamma \longrightarrow a\gamma$
- solar axion search: $\gamma\gamma \longrightarrow a \longrightarrow \gamma\gamma$



expt sensitive to cosmologically subdominant a

Current experimental limits



ADMX starting to probe the QCD axion of micro-eV mass

Strategies for WIMP Detection

- direct detection (DD): measure WIMPs scattering off a target

  go underground to beat cosmic ray bgnd

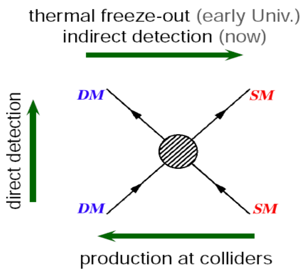
- indirect detection (ID):
  - HE neutrinos from the Sun (or Earth)

    WIMPs get trapped in Sun's core, start pair annihilating, only ν's escape
  - antimatter (e^+, $\bar{p}$, $\bar{D}$) from WIMP pair-annihilation in the MW halo

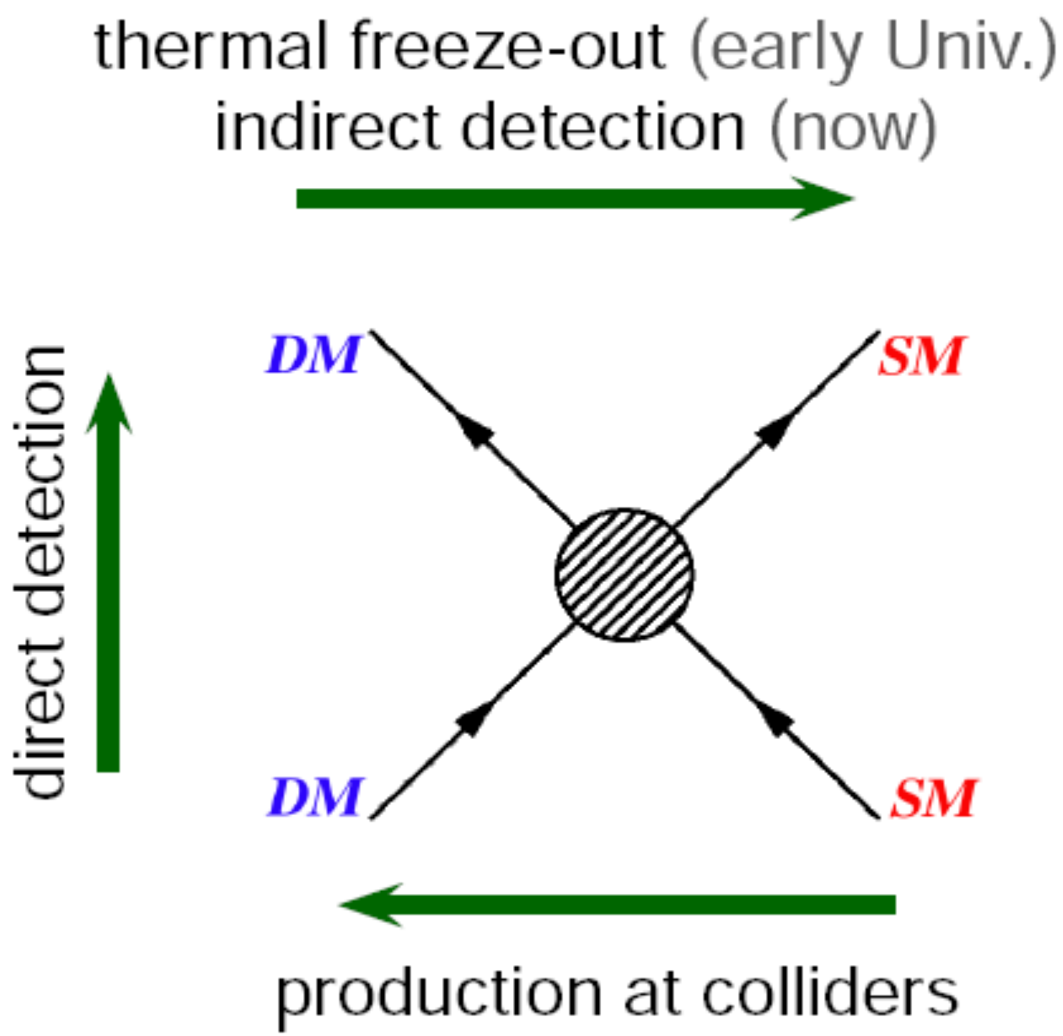
    from within a few kpc
  - gamma rays from WIMP pair-annihilation in the Galactic center

    depending on DM distribution in the GC
  - other ideas: traces of WIMP annihilation in dwarf galaxies, in rich clusters, etc

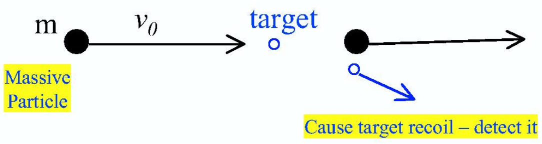
    more speculative



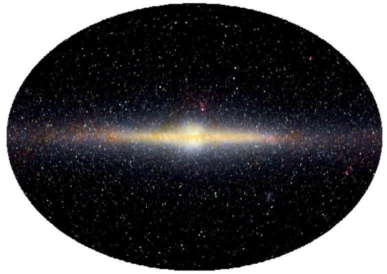
- the LHC


thermal freeze-out (early Univ.)
indirect detection (now)
direct detection
DM
SM
DM
SM
production at colliders

Direct detection



MW is immersed in a halo of WIMPs



- local density: $\rho_\chi \simeq 0.3\,\mathrm{GeV/cm^3}$
- velocity $v \sim 270\,\mathrm{km/sec}$, Maxwellian
- flux

$$\Phi = n_\chi v = 10^{10}\,\frac{\mathrm{WIMPs}}{\mathrm{m^2 sec}}\left(\frac{\rho_\chi}{0.3\,\mathrm{GeV/cm^3}}\right)\left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{v}{270\,\mathrm{km/sec}}\right)$$

- energy deposit $\sim m_\chi v^2/2 \sim 10 - 100\,\mathrm{keV}$ tiny!!!
- detection cross section $\frac{d\sigma}{dq} = G_F^2 \frac{C}{\pi v^2} F^2(q)$ $F(q)$– nuclear form factor

Non-relat. Majorana WIMP: effectively two types of interactions:

- spin independent (SI, or scalar)

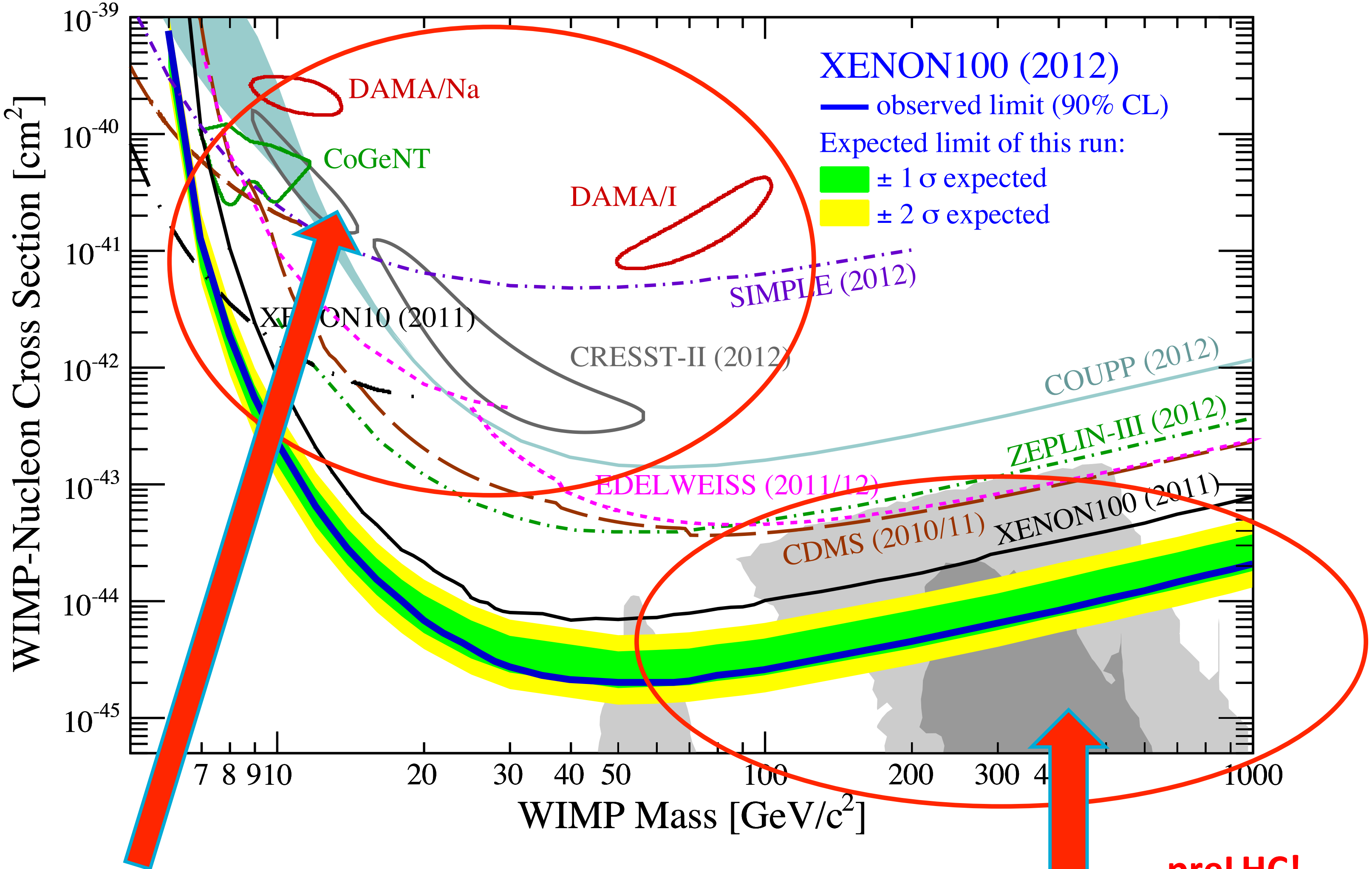
target: nucleus X_Z^A

$\frac{d\sigma^{\mathrm{SI}}}{dq} \propto A^2$ $\Leftarrow$ coherent enhancement $q \to 0:$ σ_p^{SI}

- spin dependent (SD, or axial)

$\frac{d\sigma^{\mathrm{SD}}}{dq} \propto J$ $q \to 0:$ $\sigma_p^{\mathrm{SD}}, \sigma_n^{\mathrm{SD}}$ J – total spin of target nucleus

Direct Detection AD 2011 - Before LHC



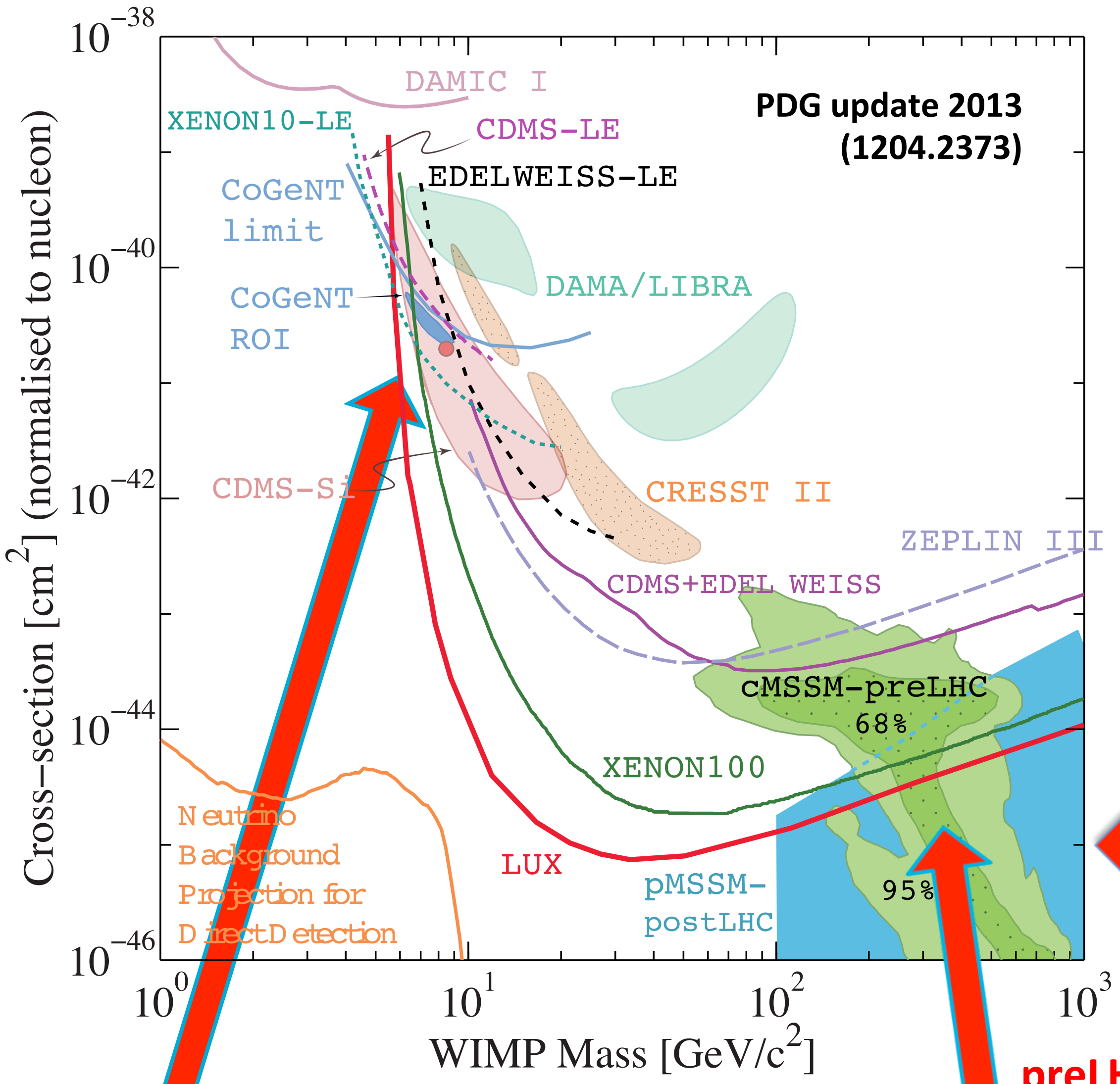
preLHC!

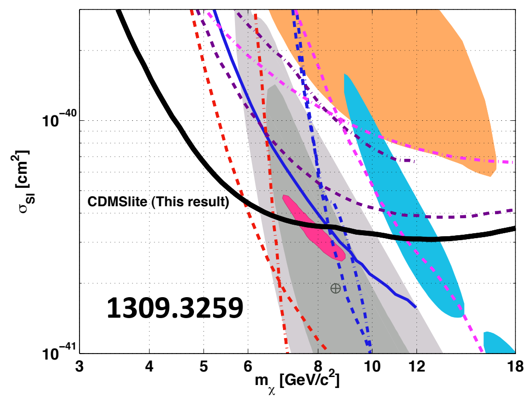
Confusion region

motivated by theory (SUSY)

MasterCode, BayesFITS

Direct Detection Nov. 2013





LHC: theory region has moved down and right

in a very specific way

Smoking gun of SUSY?

preLHC!

motivated by theory (SUSY)

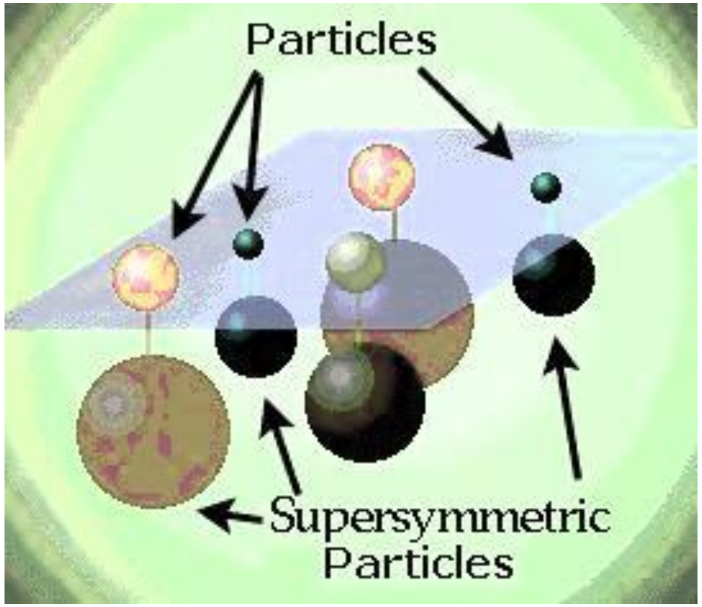
MasterCode, BayesFITS

Confusion region gone

Supersymmetry

Symmetry among particles

bosons <-> fermions

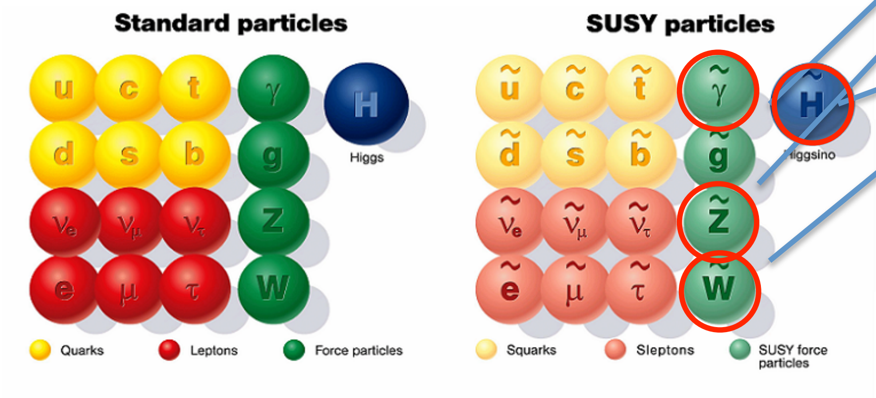


Supersymmetric dark matter?

LSP – Lightest SUSY particle:

- **Weakly interacting**

  Neutral (electric+color)
- **Massive**
- **Stable (R-parity)**



Possible candidates for LSP:

- **Part of ordinary SUSY spectrum:**

Neutralino: mass state of bino, wino, higgsinos

Sneutrino – not good (LEP, DM searches)

- If add gravity: **gravitino** LSP
- If add axion: **axino** LSP

Neutralino of SUSY – Prime Suspect

neutralino χ = lightest mass eigenstate
of neutral gauginos $\widetilde{B}$ (bino), $\widetilde{W}_3^0$ (wino) and neutral higgsinos $\widetilde{H}_t^0$, $\widetilde{H}_b^0$
Majorana fermion ($\chi^c = \chi$)

most popular candidate

- part of a well-defined and well-motivated framework of SUSY
- calculable
- relic density: $\Omega_\chi h^2 \sim 0.1$ from freeze-out (...more like $10^{-4} - 10^3$)
- stable with some discrete symmetry (e.g., R-parity or baryon parity)
- testable with today's experiments (DD, ID, LHC)
- ...no obviously superior competitor (both to SUSY and to χ) exists

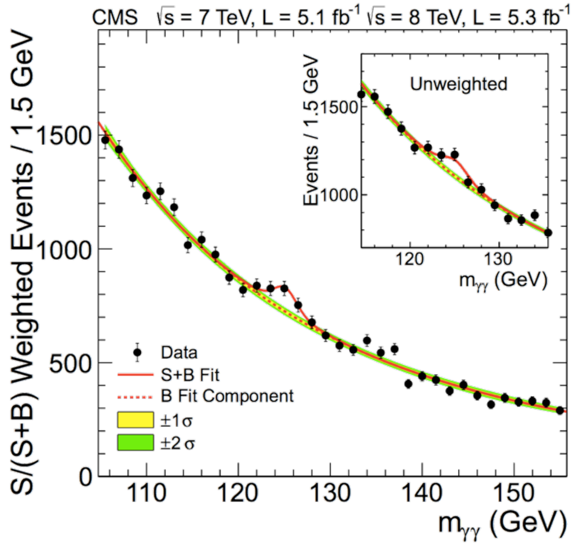
Don't forget:

- multitude of SUSY-based models: general MSSM, CMSSM, split SUSY, MNMSSM, $SO(10)$ GUTs, string inspired models, etc, etc
- neutralino properties often differ widely from model to model

neutralino = stable, weakly interacting, massive ⇒ WIMP

Main news from the LHC so far…

- **SM-like Higgs particle at ~126 GeV**



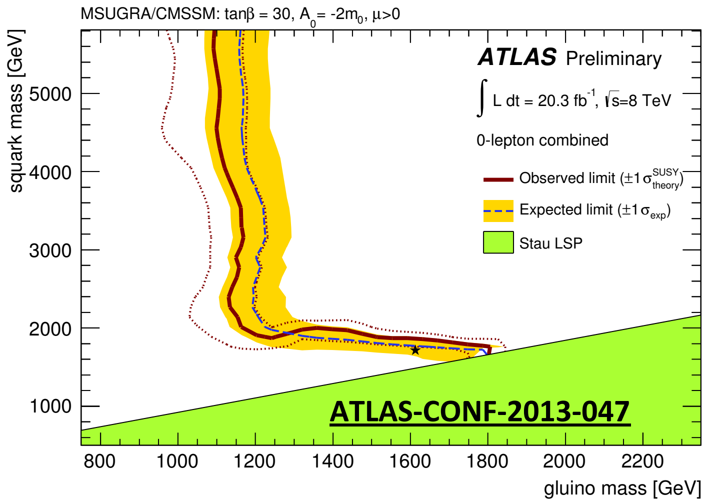
- **No (convincing) deviations from the SM**

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{LHCb}} = (2.9^{+1.1}_{-1.0}) \times 10^{-9}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{CMS}} = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$

- **Stringent lower limits on superpartner masses**



SUSY masses pushed to 1 TeV+ scale…

…and from the media…

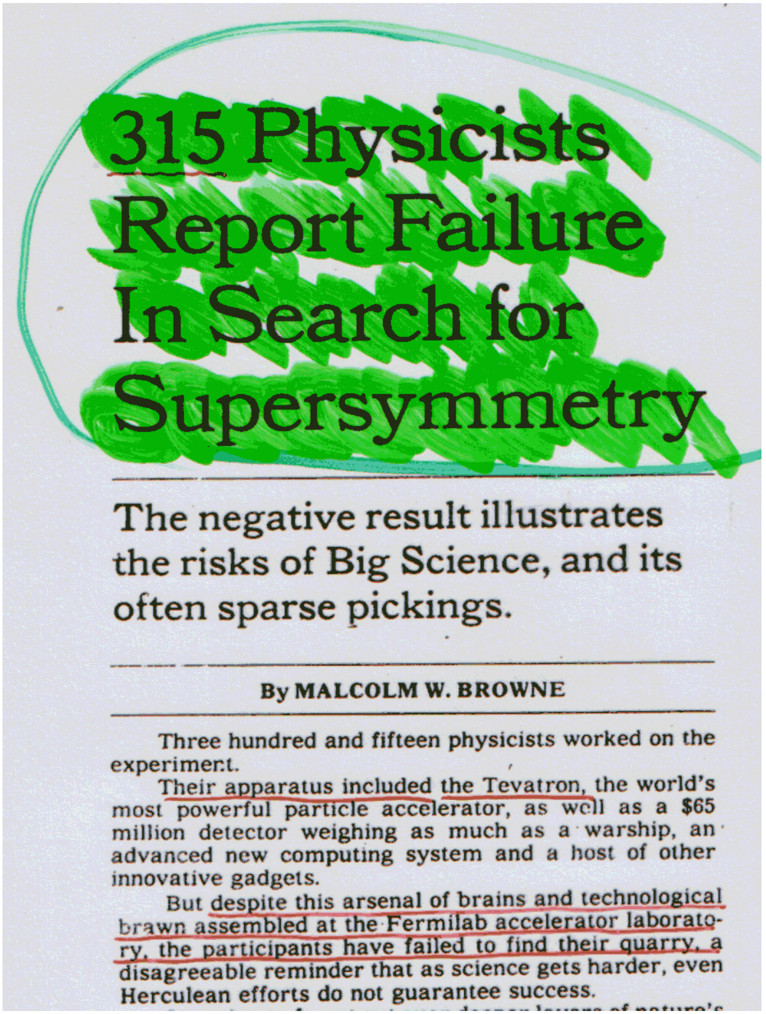
Is Supersymmetry Dead?

The grand scheme, a stepping-stone to string theory, is still high on physicists' wish lists. But if no solid evidence surfaces soon, it could begin to have a serious PR problem

SCIENTIFIC AMERICAN™

April 2012

Nothing new…



315 Physicists Report Failure In Search for Supersymmetry

The negative result illustrates the risks of Big Science, and its often sparse pickings.

By MALCOLM W. BROWNE

Three hundred and fifteen physicists worked on the experiment.

Their apparatus included the Tevatron, the world's most powerful particle accelerator, as well as a $65 million detector weighing as much as a warship, an advanced new computing system and a host of other innovative gadgets.

But despite this arsenal of brains and technological brawn assembled at the Fermilab accelerator laboratory, the participants have failed to find their quarry, a disagreeable reminder that as science gets harder, even Herculean efforts do not guarantee success.

CDF, ~2003

Assertions about SUSY

WRONG

- **SUSY can explain everything**

  (Eg. Pamela e^+ excess)

- **SUSY has been discovered!**

- **SUSY has been ruled out!**

RIGHT

- **SUSY cannot be ruled out. It can only be discovered…**

  (… or abandoned)

- **Motivation for SUSY has become stronger**

  Light Higgs!

SUSY is not only shy but also heavy (~1 TeV)

Status of SUSY AD 2014

Opinion I:

SUSY is almost dead!

Opinion II:

SUSY is more likely than ever!

The 126 GeV SM-Like Higgs Boson

A blessing or a curse for SUSY?

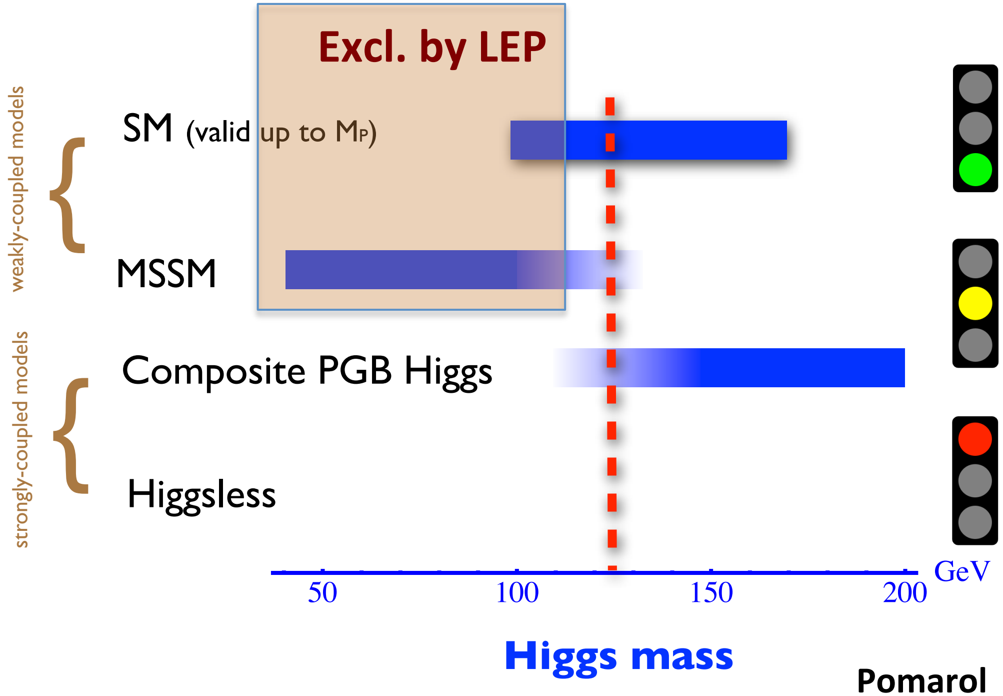
The 126 GeV Higgs Boson and SUSY

A blessing…

- Fundamental scalar --> SUSY
- Light and SM-like --> SUSY

Low energy SUSY prediction: Higgs mass up to ~135 GeV

Constrained SUSY prediction: SM-like Higgs with mass up to ~130 GeV

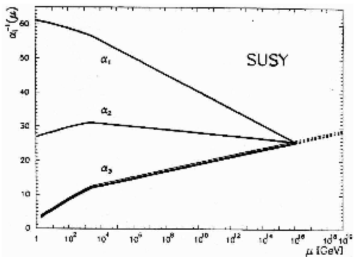


Pomarol

SUSY: Constrained or Not?

- **Constrained:**

Low-energy SUSY models with grand-unification relations among gauge couplings and (soft) SUSY mass parameters



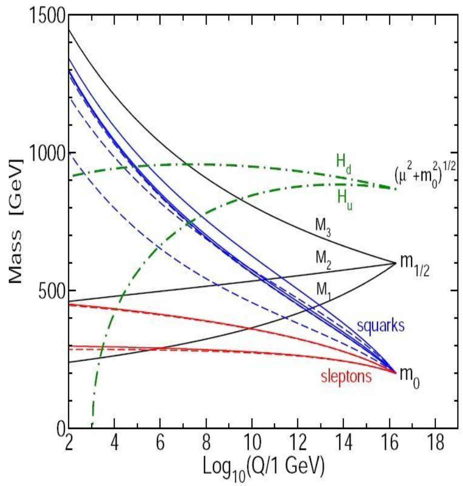


figure from hep-ph/9709356

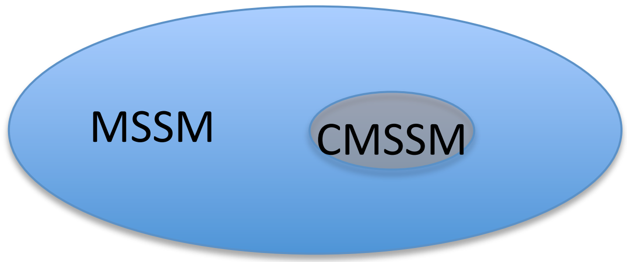
Virtues:
- **Well-motivated**
- **Predictive (few parameters)**
- **Realistic**

Many models:
- **CMSSM (Constrained MSSM): 4+1 parameters**
- **NUHM (Non-Universal Higgs Model): 6+1**
- **CNMSSM (Constrained Next-to-MSSM) 5+1**
- **CNMSSM-NUHM: 7+1**
- **etc**

- **Phenomenological:**

Supersymmetrized SM…

Features:
- **Many free parameters**
- **Broader than constrained SUSY**



Many models:
- **general MSSM – over 120 params**
- **MSSM + simplifying assumptions**
- **pMSSM: MSSM with 19 params**
- **p9MSSM, p12MSSM, pnMSSM, …**

Constrained Minimal Supersymmetric Standard Model (CMSSM)

G. L. Kane, C. F. Kolda, L. Roszkowski and J. D. Wells, Phys. Rev. D 49 (1994) 6173

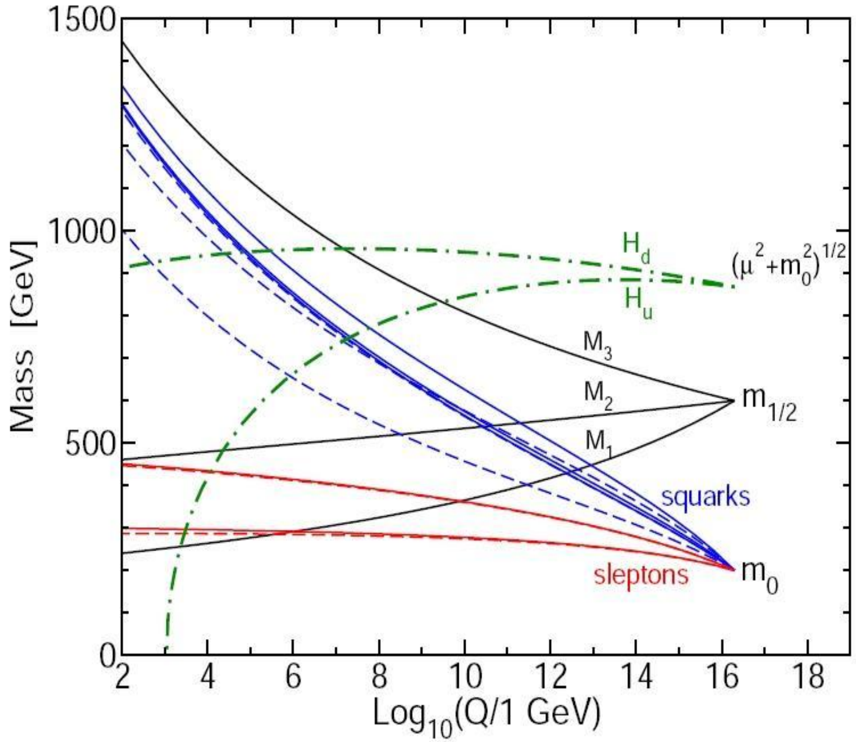


figure from hep-ph/9709356

At $M_{\mathrm{GUT}} \simeq 2 \times 10^{16}$ GeV:

- gauginos $M_1 = M_2 = m_{\tilde{g}} = m_{1/2}$
- scalars $m^2_{\tilde{q}_i} = m^2_{\tilde{l}_i} = m^2_{H_b} = m^2_{H_t} = m_0^2$
- 3–linear soft terms $A_b = A_t = A_0$
- radiative EWSB $\mu^2 = \frac{m^2_{H_b} - m^2_{H_t}\tan^2\beta}{\tan^2\beta - 1} - \frac{m_Z^2}{2}$
- five independent parameters: $m_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)$
- well developed machinery to compute masses and couplings

In general supersymmetric SM too many free parameters

How to compare theory with experiment

- **Rigid step-function application of limits/allowed ranges (e.g. DM relic abundance, etc)** — **Mahmoudi et al, Hewett et al, …**
- **Frequentist (chi^2-based)** — **MasterCode, Fittino, …**
- **Bayesian** — **BayesFITS, Allanach, SuperBayes, Balazs,…**

Frequentist: “probability is the number of times the event occurs over the total number of trials, in the limit of an infinite series of equiprobable repetitions”

Bayesian: “probability is a measure of the degree of belief about a proposition”

Both F and B are based on the likelihood function.

The Likelihood function

Central object: Likelihood function

- <u>**Positive measurements:**</u>

Take a single observable $\xi(m)$ that has been measured (e.g., M_W)

- c – central value, σ – standard exptal error
- define

$$\chi^2 = \frac{[\xi(m)-c]^2}{\sigma^2}$$

- assuming Gaussian distribution ($d \to (c, \sigma)$):

$$\mathcal{L} = p(\sigma, c|\xi(m)) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{\chi^2}{2}\right]$$

- when include theoretical error estimate τ (assumed Gaussian):

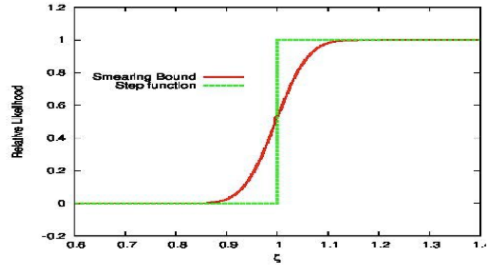
$$\sigma \to s = \sqrt{\sigma^2 + \tau^2}$$

TH error "smears out" the EXPTAL range

- for several uncorrelated observables (assumed Gaussian):

$$\mathcal{L} = \exp\left[-\sum_i \frac{\chi_i^2}{2}\right]$$

- <u>**Limits:**</u>



- Smear out bounds.
- Add theory error.

- <u>**LHC direct limits:**</u>
  - Need careful treatment. Typically use Poisson.

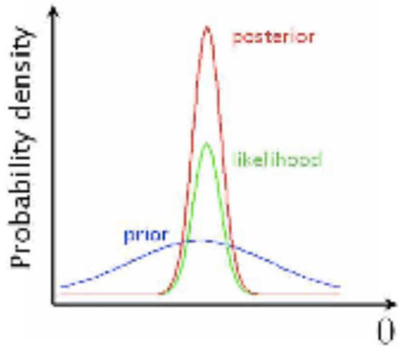
Bayesian statistics

Bayes theorem: $$\text{Posterior} = \frac{\text{Prior} \times \text{Likelihood}}{\text{Evidence}}$$

- **Prior**: what we know about hypothesis BEFORE seeing the data.
- **Likelihood**: the probability of obtaining data if hypothesis is true.
- **Posterior**: the probability about hypothesis AFTER seeing the data.
- **Evidence**: normalization constant, crucial for model comparison.

If hypothesis is a function of parameters, then posterior becomes posterior probability function (pdf).

Posterior → credible regions at chosen CL



Minimum chi2 approach: find best-fit and draw confidence regions about it

The 126 GeV SM-Like Higgs Boson

A blessing or a curse for SUSY?

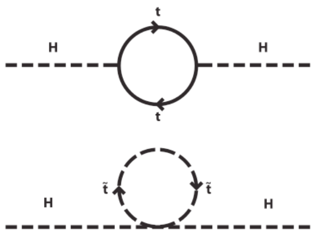
The 126 GeV Higgs Boson and SUSY

A curse…

In SUSY Higgs mass is a calculated quantity

- **1 loop correction**

$$\Delta m_h^2 = \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{M_{\rm SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12M_{\rm SUSY}^2}\right)\right]$$



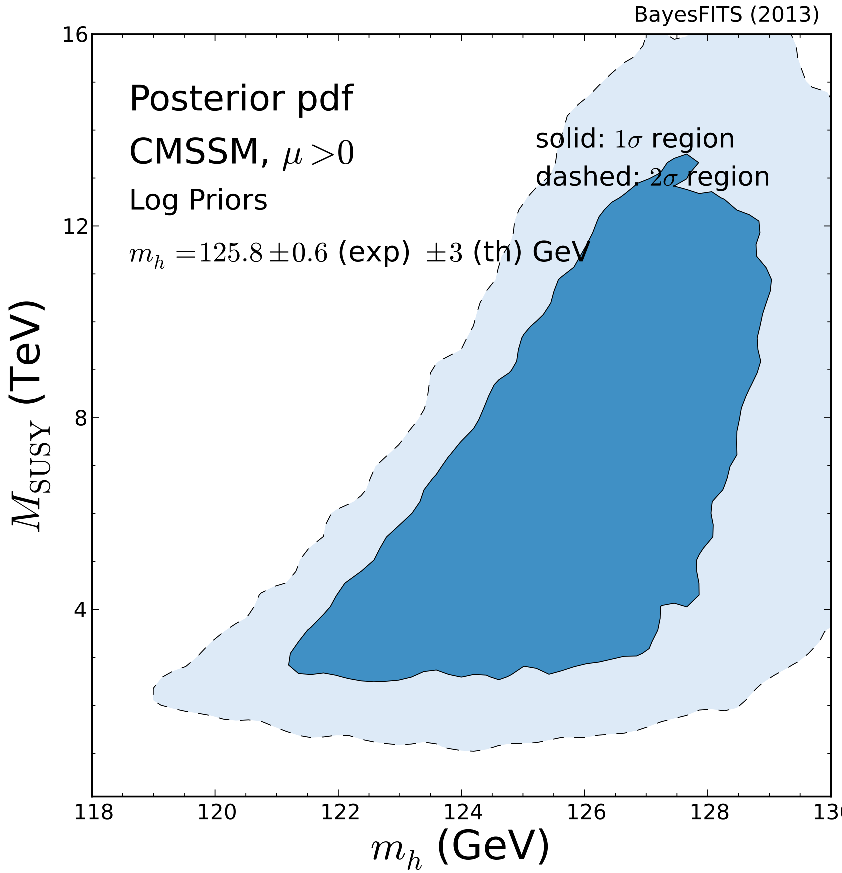
$$X_t = A_t - \mu\cot\beta$$

$$M_{\rm SUSY} \equiv \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$$

Only m_h~126 GeV and CMS lower bounds on SUSY applied here.

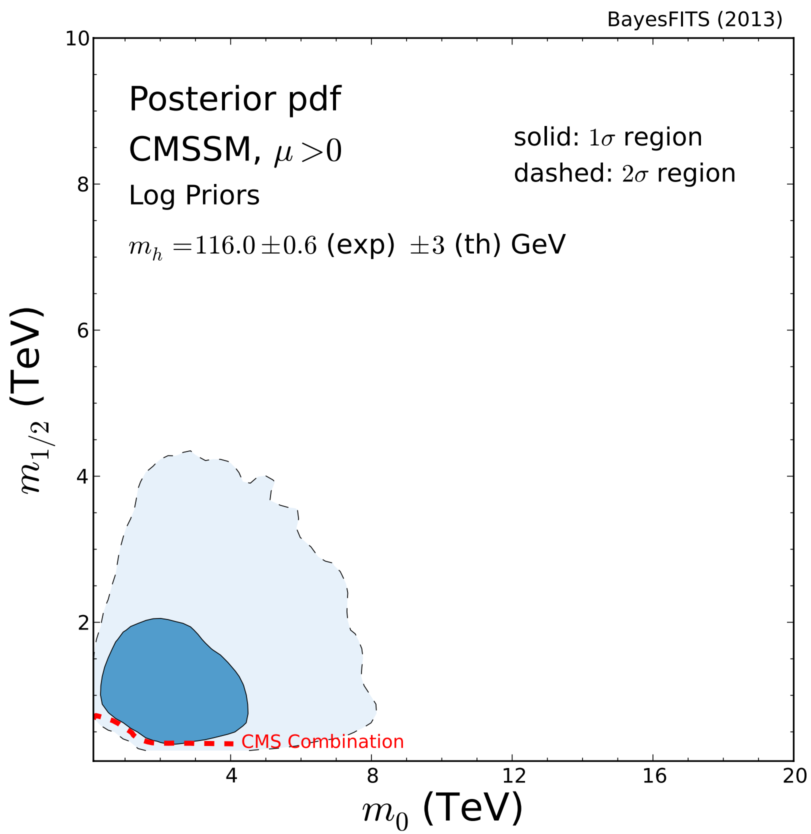
$$\mathcal{L} \sim e^{\frac{(m_h - 125.8\,{\rm GeV})^2}{\sigma^2+\tau^2}}$$

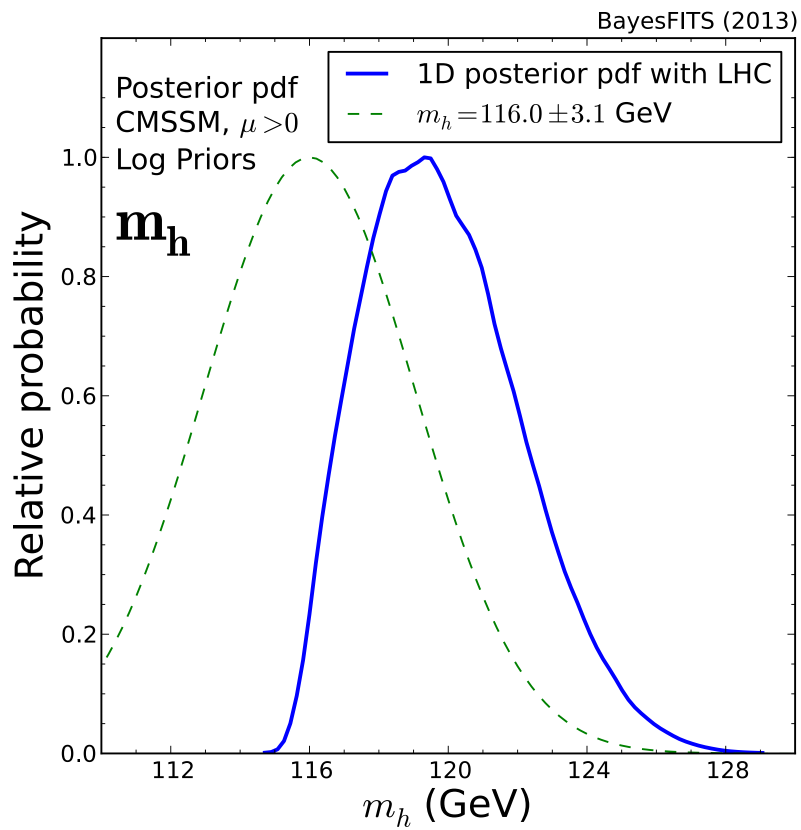
$\sigma = 0.6$ GeV, $\tau = 2$ GeV



126 GeV Higgs -> multi-TeV SUSY

If m_h were, say, 116 GeV...





... 116 GeV Higgs would imply significant tension with LHC bounds on SUSY

... 126 GeV mass is fully consistent with them

The 126 GeV SM-Like Higgs Boson

A blessing or a curse for DM?

CMSSM: numerical scans

- **Perform random scan over 4 CMSSM +4 SM (nuisance) parameters <u>simultaneously</u>**

- Very wide ranges:

1302.5956

$$100\,\mathrm{GeV} \leq m_0 \leq 20\,\mathrm{TeV}$$
$$100\,\mathrm{GeV} \leq m_{1/2} \leq 10\,\mathrm{TeV}$$
$$-20\,\mathrm{TeV} \leq A_0 \leq 20\,\mathrm{TeV}$$
$$3 \leq \tan\beta \leq 62$$

- Use Nested Sampling algorithm to evaluate posterior
- Use 4 000 live points

Nuisance	Description	Central value ± std. dev.	Prior Distribution
M_t	Top quark pole mass	$173.5 \pm 1.0\,\mathrm{GeV}$	Gaussian
$m_b(m_b)_{\mathrm{SM}}^{\overline{MS}}$	Bottom quark mass	$4.18 \pm 0.03\,\mathrm{GeV}$	Gaussian
$\alpha_s(M_Z)^{\overline{MS}}$	Strong coupling	0.1184 ± 0.0007	Gaussian
$1/\alpha_{\mathrm{em}}(M_Z)^{\overline{MS}}$	Inverse of em coupling	127.916 ± 0.015	Gaussian

Use Bayesian approach (posterior)

Hide and seek with SUSY

The experimental measurements that we apply to constrain the CMSSM's parameters. Masses are in GeV.

Measurement	Mean or Range	Error: (Exp., Th.)	Distribution
Combination of:			
CMS razor 4.4/fb , $\sqrt{s} = 7\,\text{TeV}$	See text	See text	Poisson
CMS α_T 11.7/fb , $\sqrt{s} = 8\,\text{TeV}$	See text	See text	Poisson
m_h by CMS	125.8 GeV	0.6 GeV, 3 GeV	Gaussian
$\Omega_\chi h^2$	0.1120	0.0056, 10%	Gaussian
$\delta\,(g-2)_\mu^{\text{SUSY}} \times 10^{10}$	28.7	8.0, 1.0	Gaussian
$\text{BR}\,(\overline{B} \to X_s\gamma) \times 10^4$	3.43	0.22, 0.21	Gaussian
$\text{BR}\,(B_u \to \tau\nu) \times 10^4$	1.66	0.33, 0.38	Gaussian
ΔM_{B_s}	$17.719\,\text{ps}^{-1}$	$0.043\,\text{ps}^{-1}$, $2.400\,\text{ps}^{-1}$	Gaussian
$\sin^2\theta_{\text{eff}}$	0.23116	0.00012, 0.00015	Gaussian
M_W	80.385	0.015, 0.015	Gaussian
$\text{BR}\,(B_s \to \mu^+\mu^-)_{\text{current}} \times 10^9$	3.2	+1.5 − 1.2, 10% (0.32)	Gaussian
$\text{BR}\,(B_s \to \mu^+\mu^-)_{\text{proj}} \times 10^9$	3.5 (3.2*)	0.18 (0.16*), 5% [0.18 (0.16*)]	Gaussian

SM value: $\simeq 3.5 \times 10^{-9}$

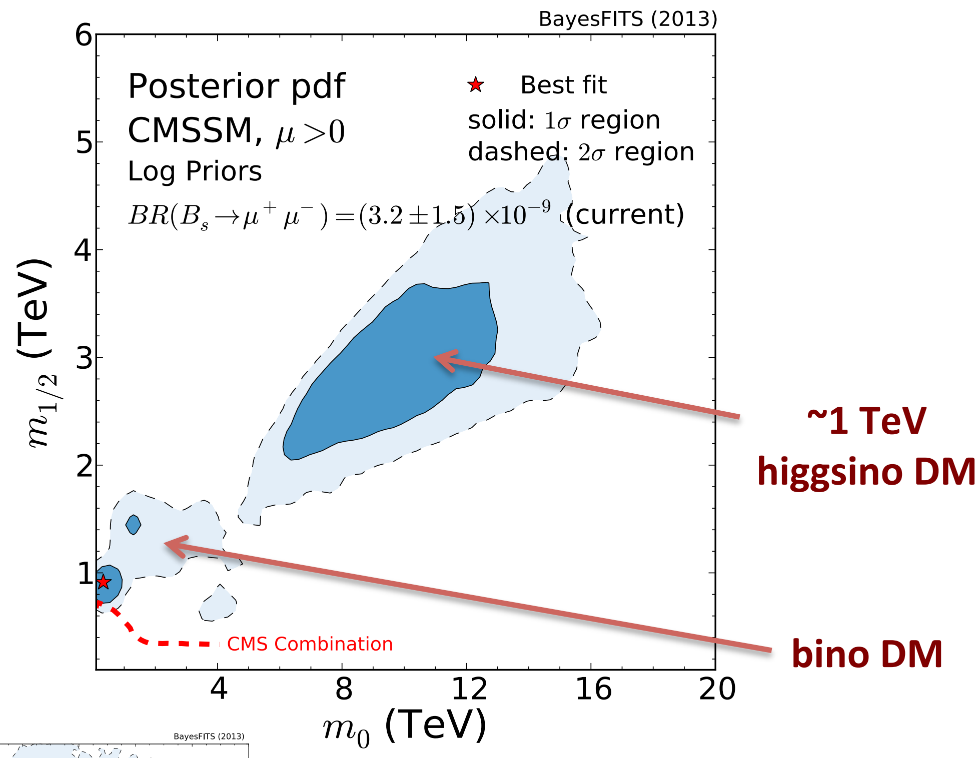
10 dof

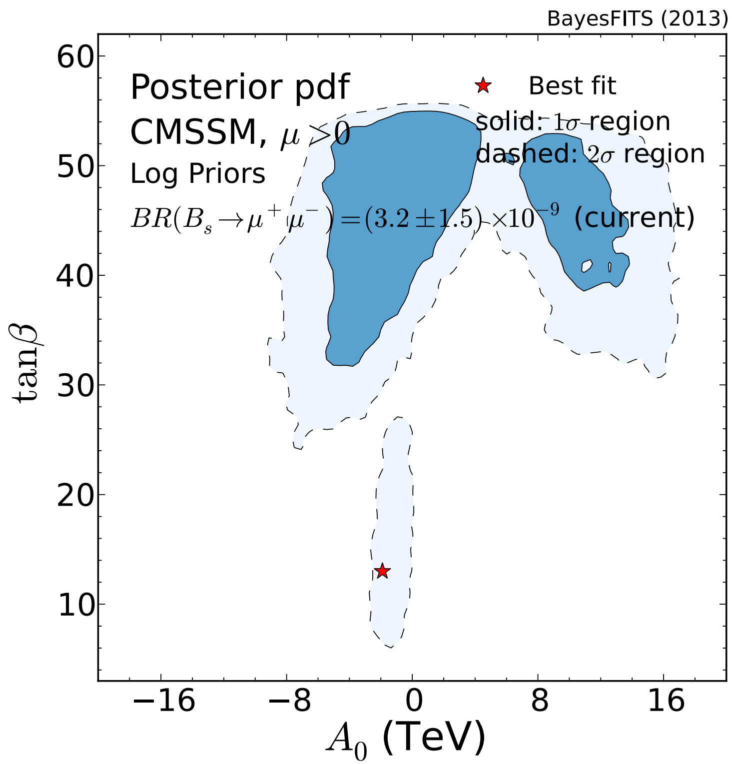
At TeV scale basically only constraints from: Higgs mass, DM relic abundance play a big role, plus some from direct limits on SUSY and from direct detection of WIMPs (if included)

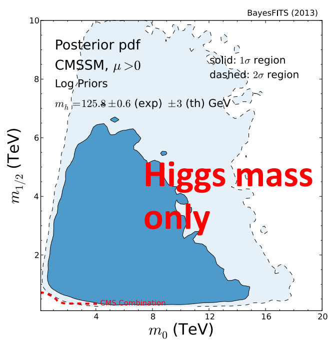
The CMSSM with DM relic density

Global scan, Bayesian
total posterior probability regions

Kowalska, LR, Sessolo,
arXiv:1302.5956



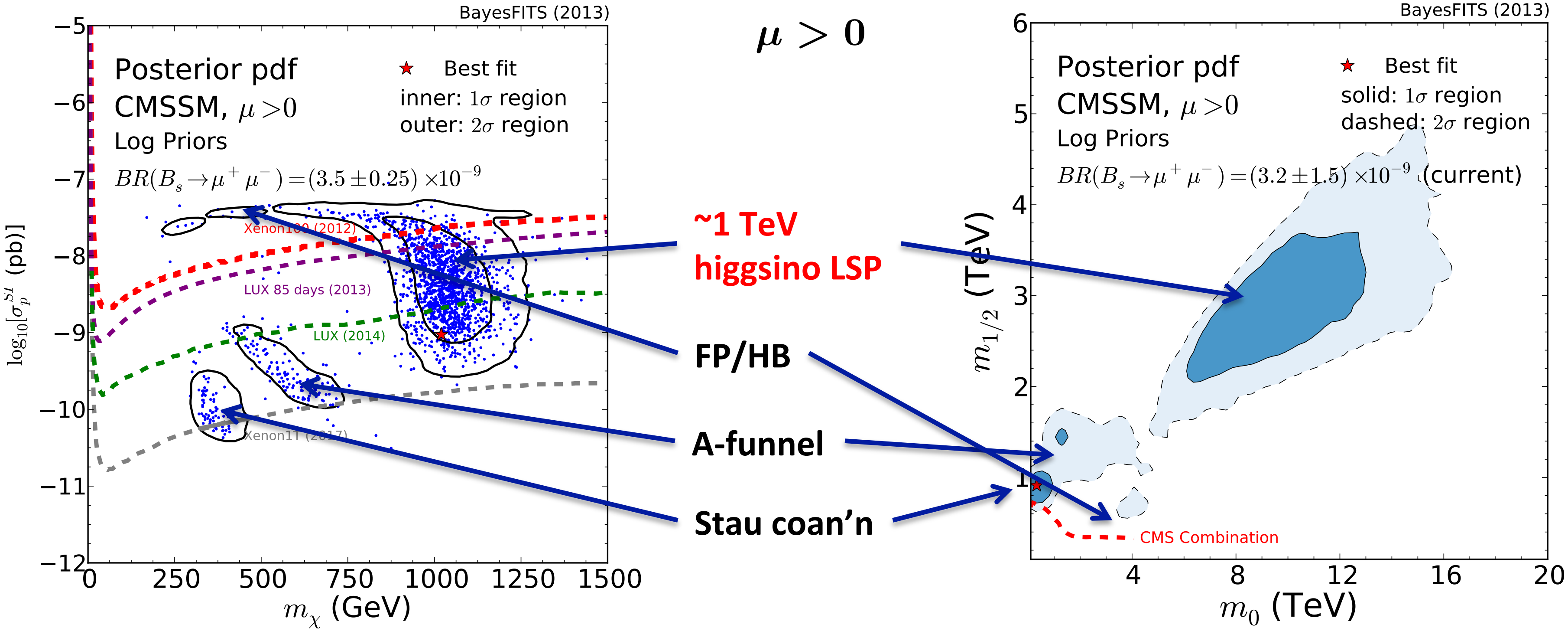




CMSSM: these are the only DM-favored regions

~1 TeV higgsino-like WIMP: implied by ~126 GeV Higgs

CMSSM and DM searches



Focus point region ruled out by LUX (tension with X100)

~1TeV higgsino DM:
exiting prospects for LUX, X100 and 1t detectors

~1 TeV higgsino DM

✧ Robust, present in many SUSY models
(both GUT-based and not)

Condition: heavy enough gauginos

When $m_{\tilde{B}} \gtrsim 1\,\mathrm{TeV}$:
easiest to achieve $\Omega_\chi h^2 \simeq 0.1$
when $m_{\tilde{H}} \simeq 1\,\mathrm{TeV}$

✧ Implied by ~126 GeV Higgs mass
and relic density

✧ Most natural

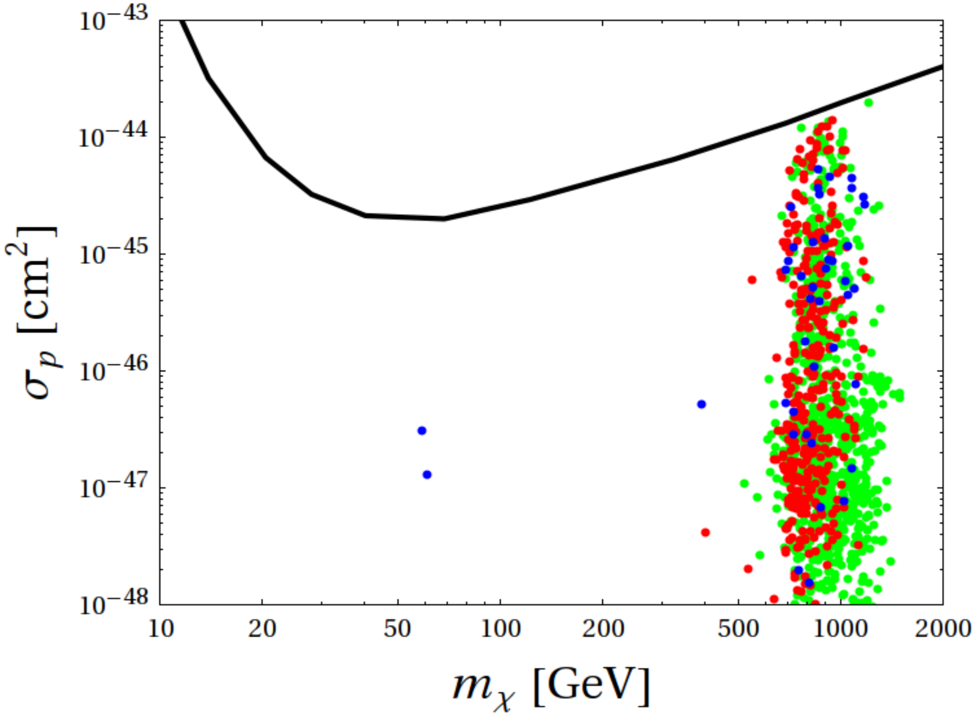
✧ Smoking gun of SUSY!?

No need to employ special mechanisms (A-funnel or coannihilation) to obtain correct relic density

… generic

e.g., Next-to-MSSM (extra singlet Higgs)

Kaminska, Ross, Schmidt-Hoberg, 1308.4168



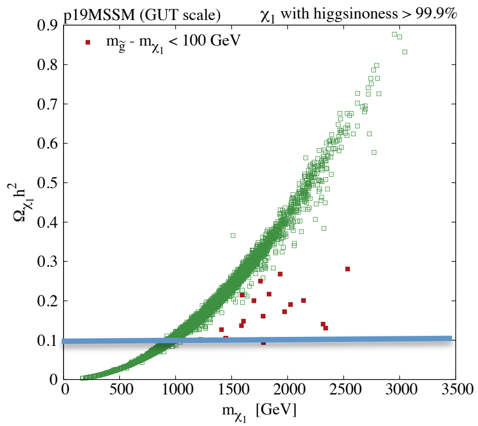
Fall and rise of higgsino DM

✧ **1991: put to grave**

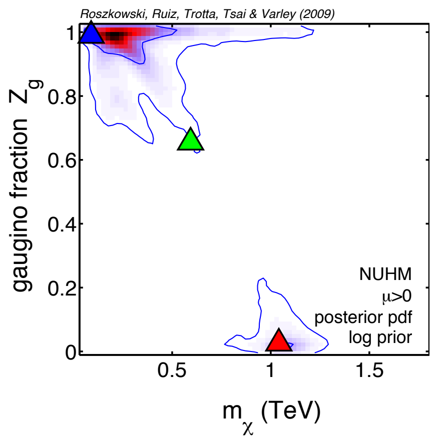
LR, PLB 262 (1991) 59: in MSSM:
- **too little DM until mass >> 1 TeV (conflict with naturalness)**
- **bino favored**

✧ **2004: first signs of being still (again?) alive**

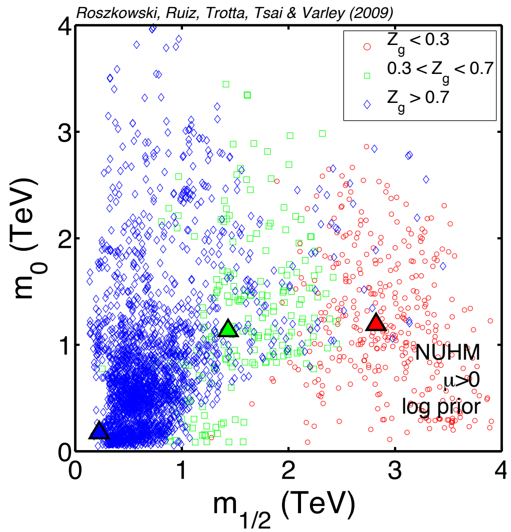
MSSM: Profumo & Yaguna, hep-ph/040703, Arkani-Hamed, Delgado, Giudice, hep-ph/0601041



✧ **2009: favored in unified SUSY at m_1/2>~2 TeV**



NUHM in 0903.1279



✧ **2012: favored by ~126 GeV Higgs mass**

CMSSM: Cabrera et al., 1212.4821
NUHM: Strege et al., 1212.2636
CMSSM & NUHM: Kowalska, et al., 1302.5956

~1 TeV higgsino DM:
NUHM: even at low m_0, CMSSM: m_0 of few TeV

Can such multi-TeV ranges of SUSY parameters be experimentally tested?

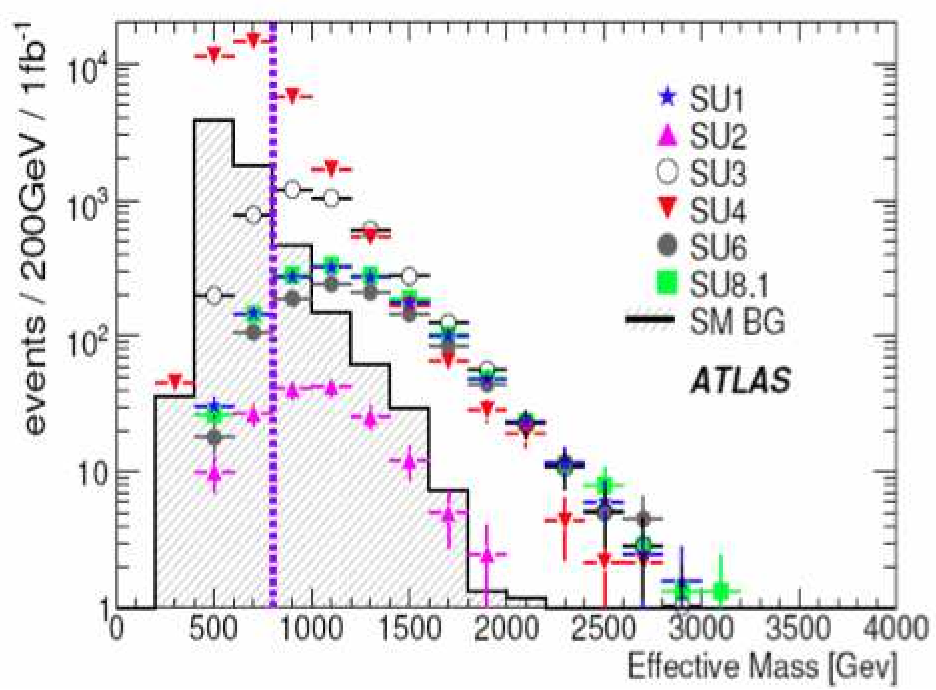
Standard SUSY at the LHC

with neutralino χ as LSP

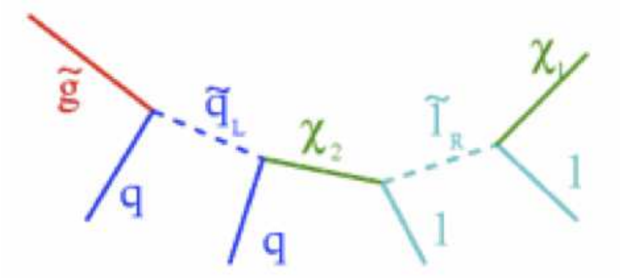
$\sqrt{s} = 7\,\mathrm{TeV}\ \ (\to 14\,\mathrm{TeV}),\ \int \mathcal{L} \gtrsim 1\,\mathrm{fb}^{-1}$

ATLAS, CMS

e.g.: 4 jet + p_T^{miss} distribution



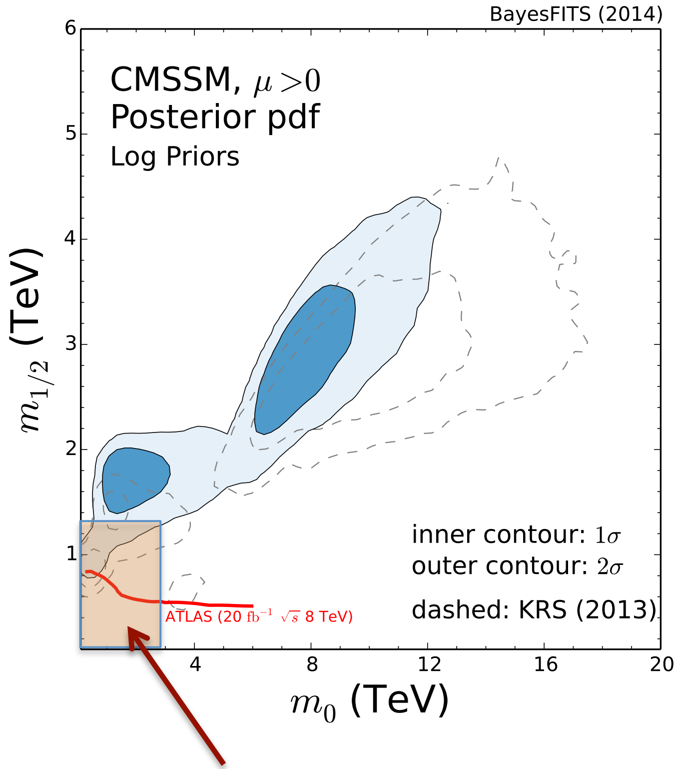
e.g.: $\tilde{g}$ cascade decay



- use end-point, E_T^{miss}, etc, to work out m_χ
- LHC: m_χ up to some $400 - 500\,\mathrm{GeV}$

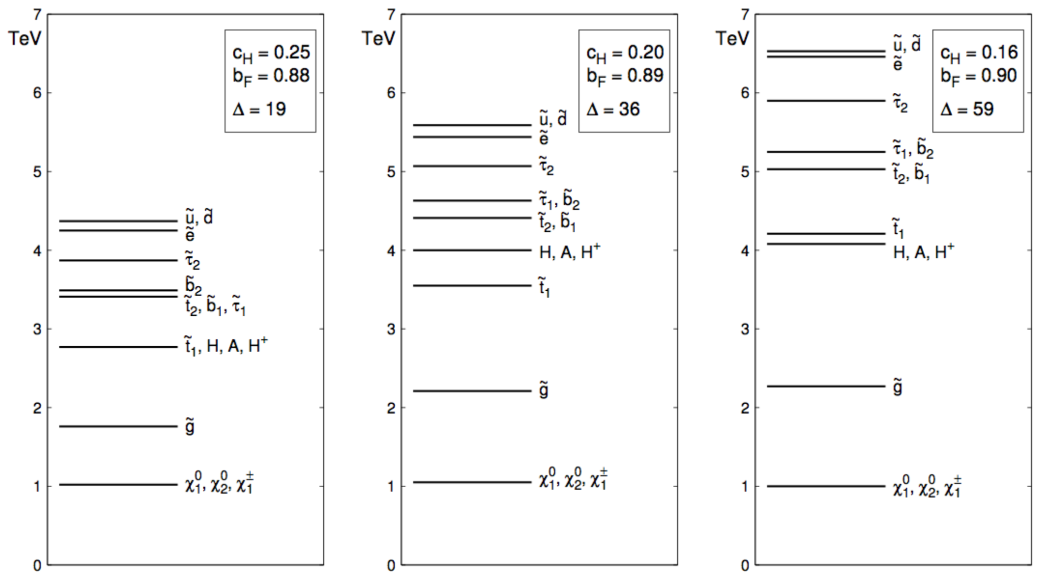
- measure as many processes as possible
- perform detailed spectroscopy, ...

The LHC?



LHC14 reach:
Gluino: ~2.7 GeV
Squarks: ~3 TeV

CMSSM: typical mass spectra: **1405.4289**



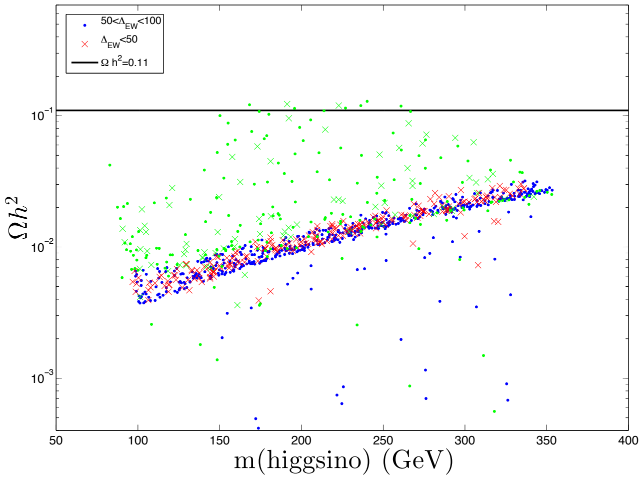
- **LHC – only stau coannihilation will be +/- covered**
- **Need a lot of luck!**

General MSSM: much lower masses allowed

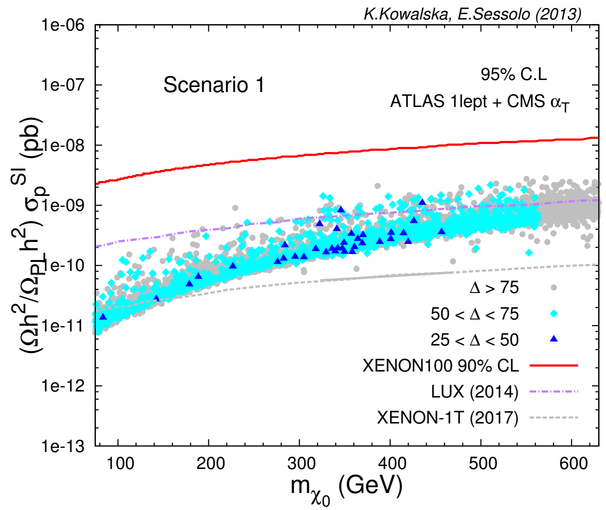
Higgsino at the LHC?

- ➢ **~1 TeV higgsino: too heavy, hopeless**
- ➢ **~200-300 GeV higgsino: motivated by low finetuning (``Natural'' SUSY)**
  - **Oh2 too low (by a factor of ~10)**
  - **Need to add another DM (axion as CDM (=co-DM))**
  - **After rescaling local density: reasonably good prospects for 1tonne DD**

1307.5790



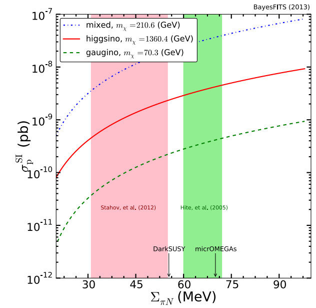
Baer, et al., 1303.3816



Monojets a LHC: prospects poor (Baer, et al.) or limited (Arbey, et al, 1311.7641)

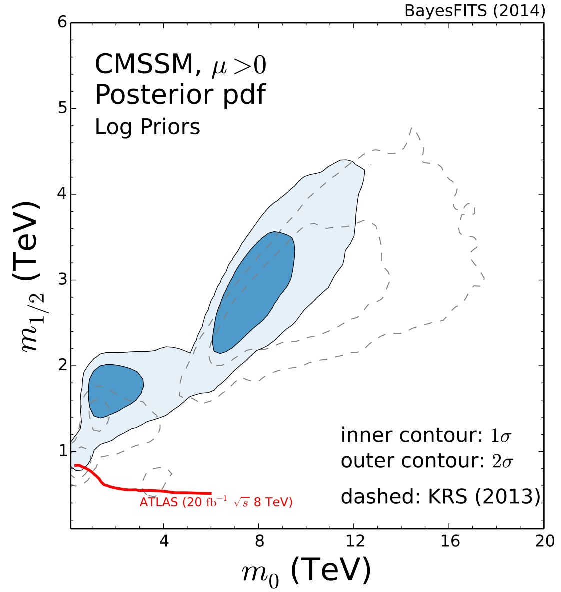
Update 2014

- Effect of 3 loop corr's to m_h: increase by ~2 GeV
- LUX limit: FP region practically excluded
- Theory sigma_p down by ~1 order of mag

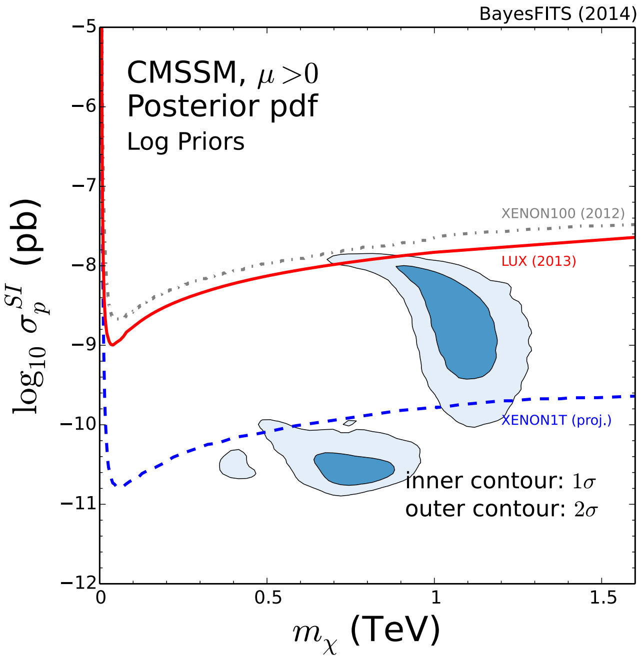


Recent (micrOmegas3.1):

$$\sigma_s = 42 \pm 5\,\mathrm{MeV} \qquad \sigma_{\pi N} = 34 \pm 2\,\mathrm{MeV}$$



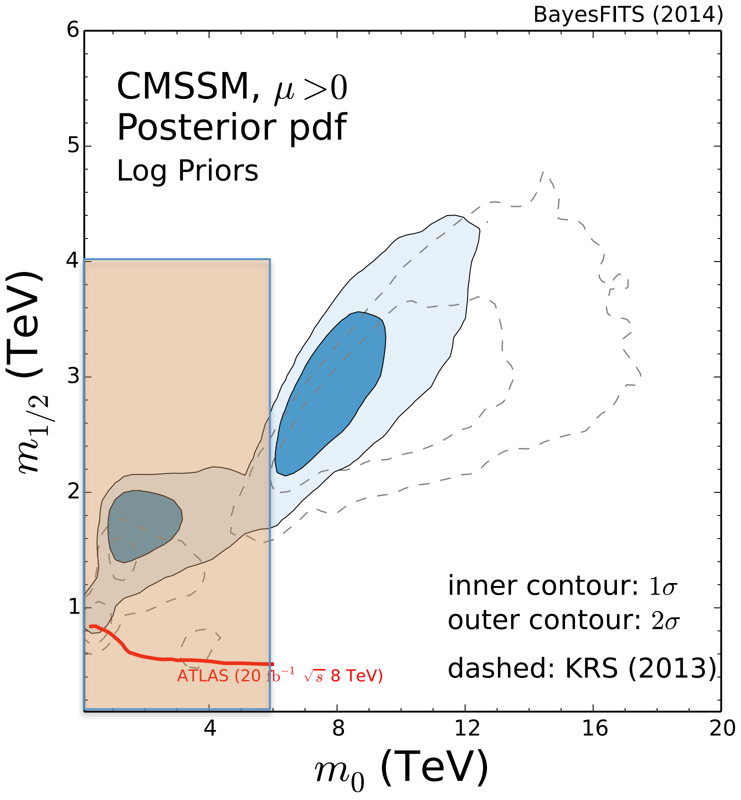
1405.4289



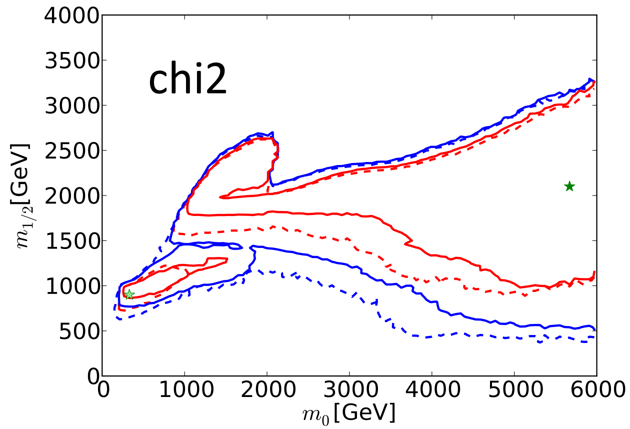
Main effects:

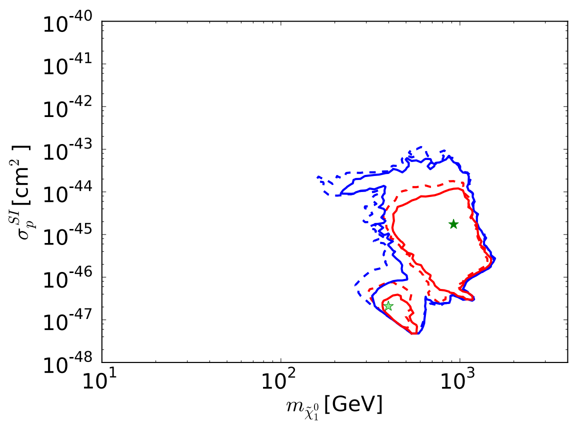
- m_0: slight shift down
- ~1 TeV higgsino still dominant
- some increase of A-funnel region
- FP region excluded

Bayesian vs chi-square analysis
(updated to include 3loop Higgs mass corrs)



Buchmueller et al [1312.5250]



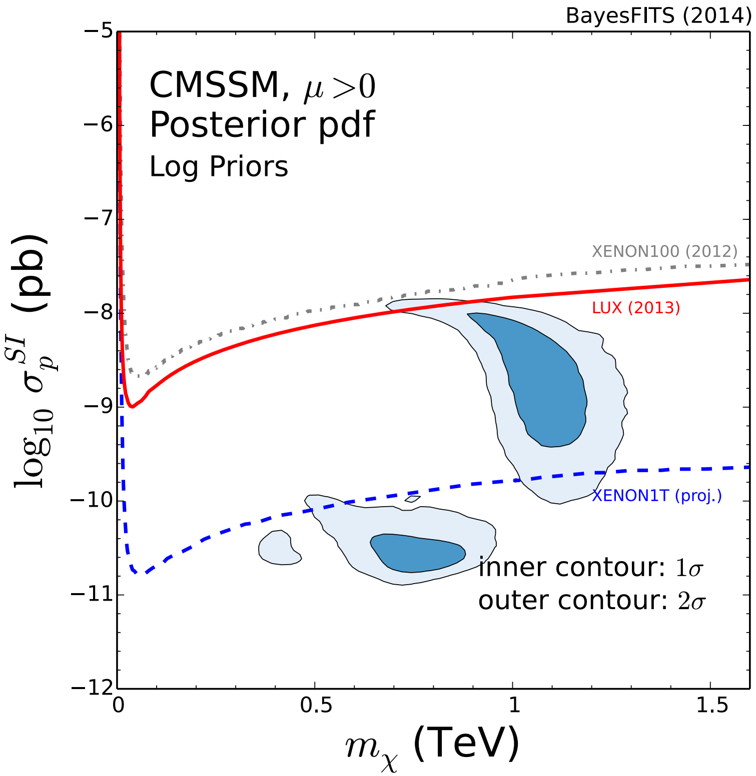


Reasonably good agreement in overlapping region

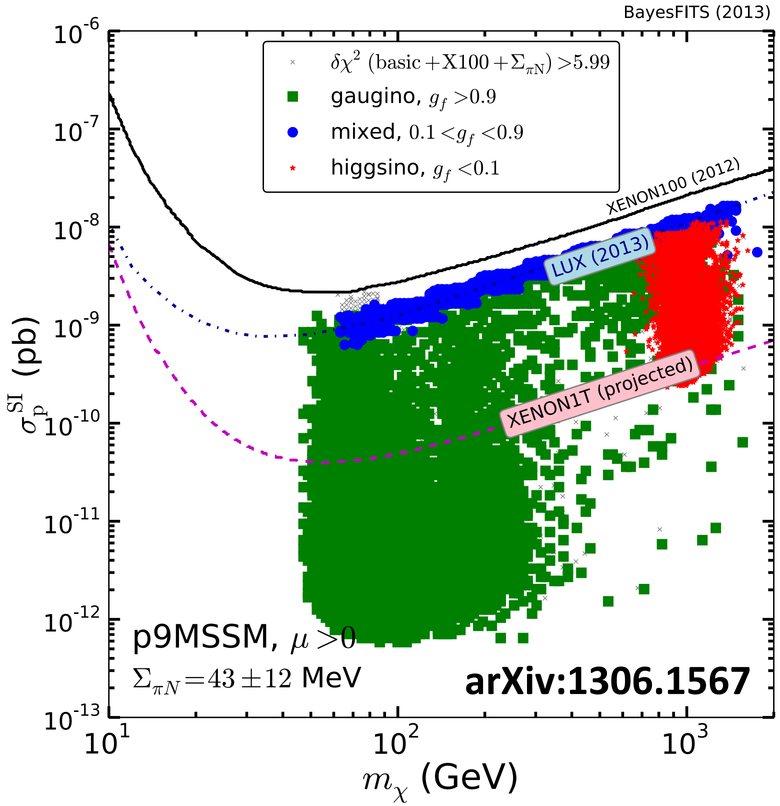
~1 TeV higgsino-like WIMP: implied by ~126 GeV Higgs -> large m1/2 and m0

Unified vs pheno SUSY

Unified SUSY (Constrained MSSM)



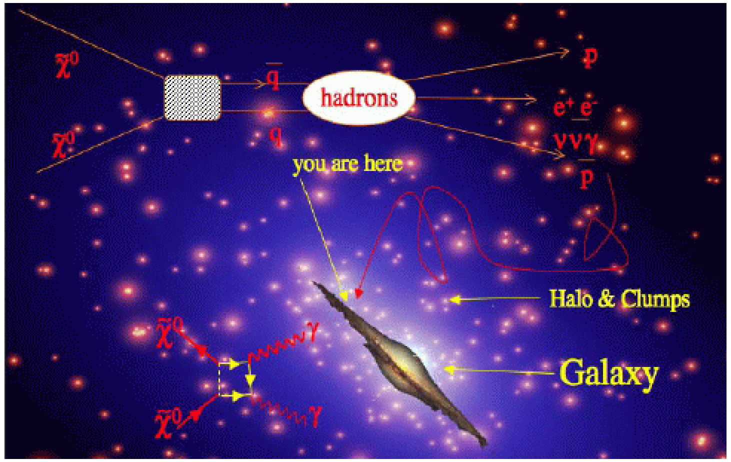
General SUSY (p9MSSM)



MSSM:

- **much bigger ranges allowed**
- **~1 TeV higgsino DM: prospects for detection similar to unified SUSY**
- **new LUX limit: started to exclude mixed (bino-higgsino) neutralino**

Indirect detection

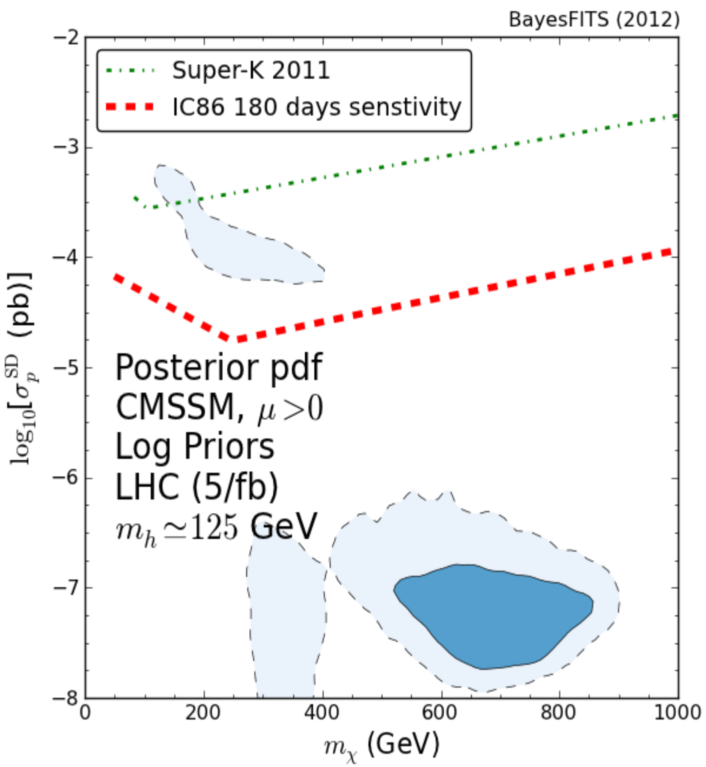


- look for traces of WIMP annihilation in the MW halo (γ's, e^+'s, $\bar{p}$, ...)
- detection prospects often strongly depend on astrophysical uncertainties (halo models, astro bgnd, ...)

Much activity:

- PAMELA
- Fermi
- neutrino telescopes, ATCs, ...

SUSY DM and neutrino flux from the Sun



apply constraints on SUSY from LHC
(including Higgs signal)

Deep Core:

$E^{th}_{DeepCore}$ = 35 GeV

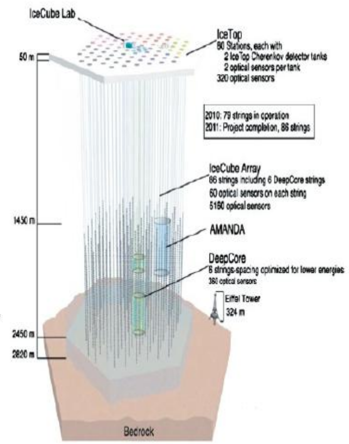
Background events: 2.5/yr

IceCube (upward and contained):

$E^{th}_{IceCube}$ = 100 GeV

Background events: (6.1 and 15.6)/yr

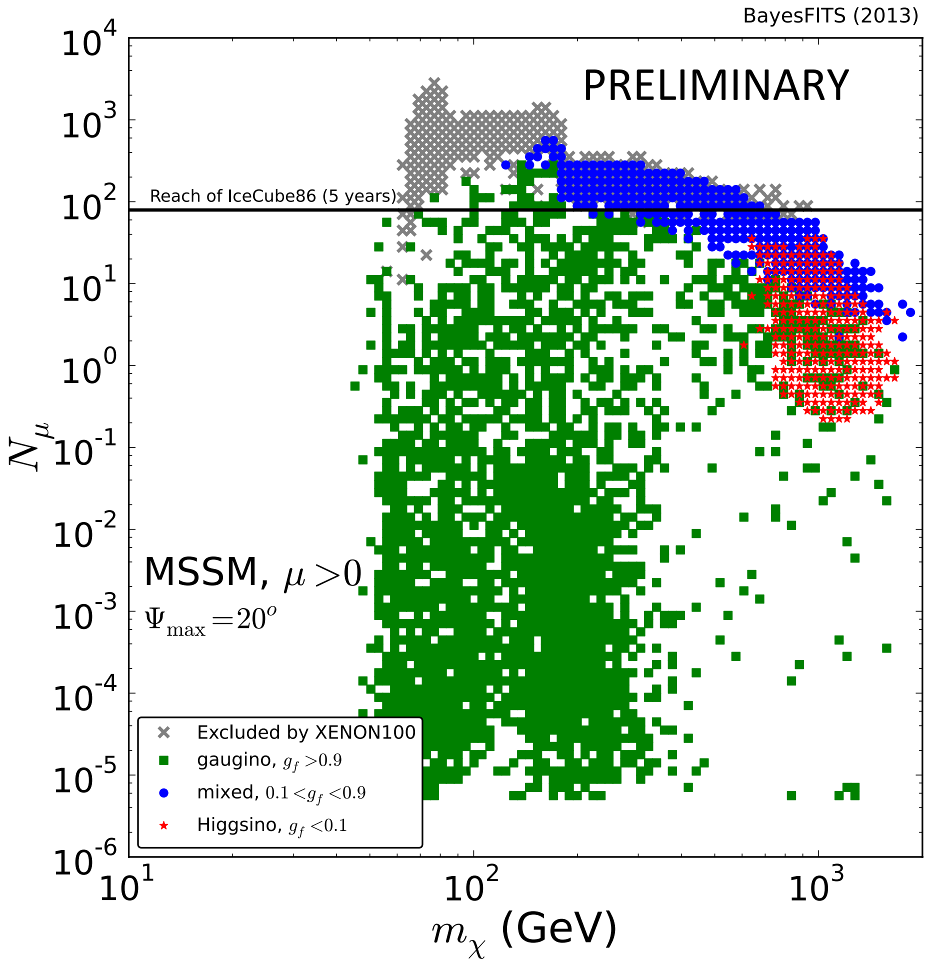
(Barger *et al.* 1004.4573 [hep-ph])



sensitivity = $\sigma \times \sqrt{\text{background} \times \text{exposure time}}$

SUSY: favored ranges far below the sensitivity of IceCube

Neutrino Telescopes and the MSSM

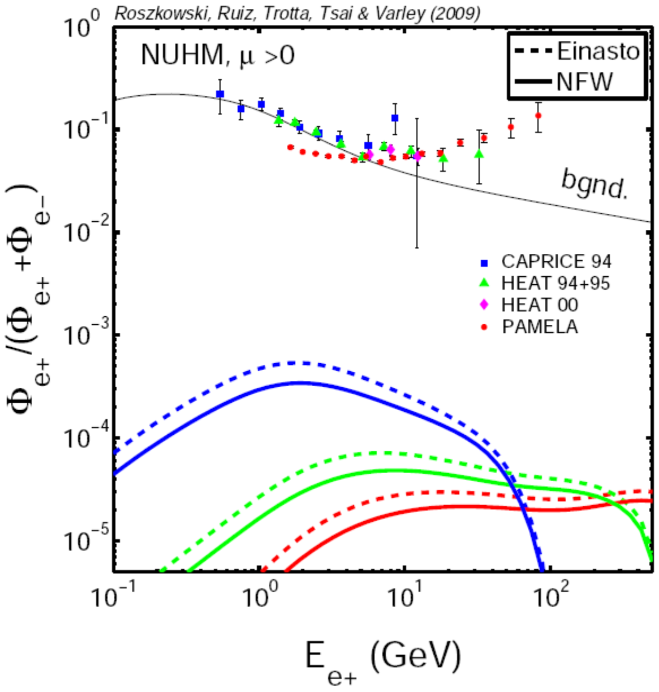


Wide scan over 9 parameters (p9MSSM)

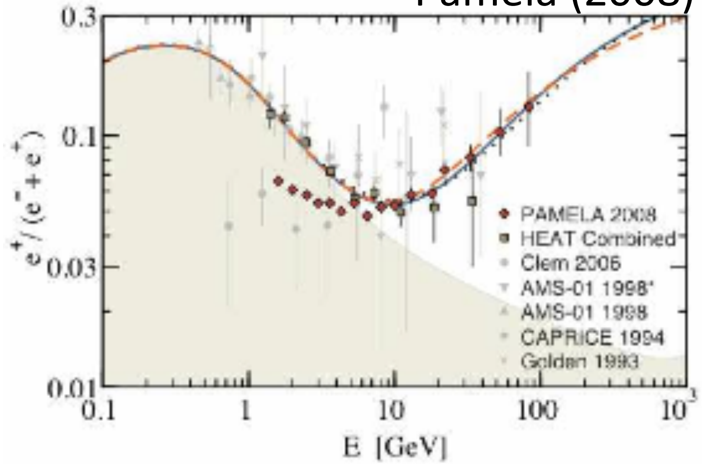
$$
\begin{aligned}
m_\chi &> 46\,\mathrm{GeV},\\
m_{\tilde{e}} &> 107\,\mathrm{GeV},\\
m_{\tilde{g}} &> 500\,\mathrm{GeV},\\
m_{\chi_1^\pm} &> 94\,\mathrm{GeV\ if\ m_{\chi_1^\pm} - m_\chi > 3\,GeV\ and\ \tan\beta < 40}\\
m_{\tilde{\mu}} &> 94\,\mathrm{GeV\ if\ m_{\tilde{\mu}} - m_\chi > 10\,GeV\ and\ \tan\beta < 40.}\\
m_{\tilde{\tau}} &> 81.9\,\mathrm{GeV\ if\ m_{\tilde{\tau}_R} - m_\chi > 15\,GeV},\\
m_{\tilde{b}_1} &> 89\,\mathrm{GeV\ if\ m_{\tilde{b}_1} - m_\chi > 8\,GeV},\\
m_{\tilde{t}_1} &> 95.7\,\mathrm{GeV\ if\ m_{\tilde{t}_1} - m_\chi > 10\,GeV}.
\end{aligned}
$$

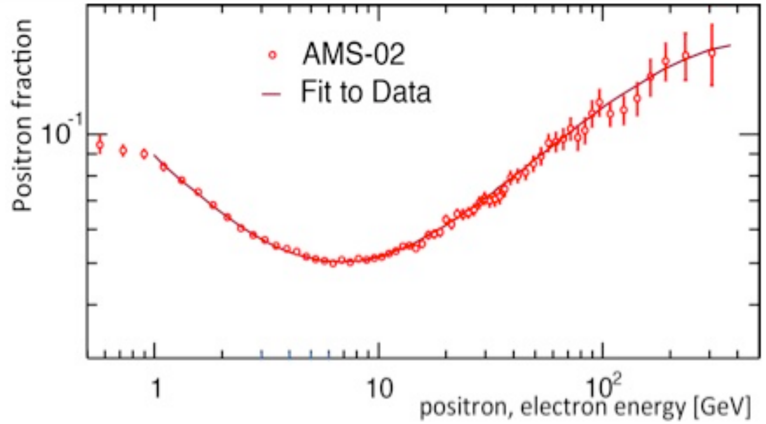
Even in the MSSM predicted neutrino rates are LOW at best

SUSY DM and positron flux



Pamela (2008)





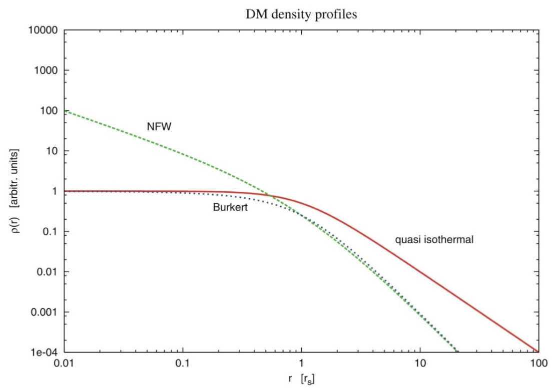
SUSY does not explain positron excess!

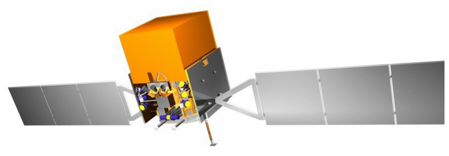
Also true for wino LSP (Hryczuk et al)

AMS may help settle the issue:

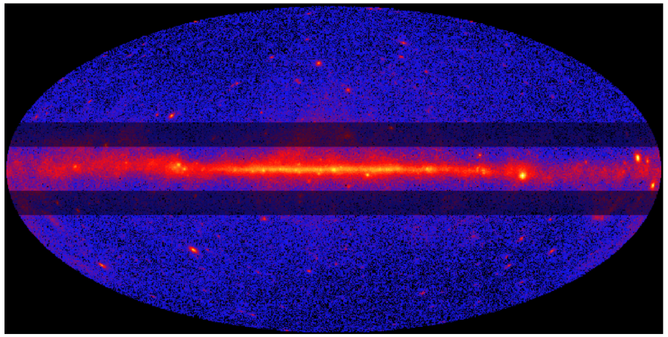
- **if isotropic: DM**
- **If directional: pulsar**

Fermi





in orbit since 2008



- full sky map in γ-ray spectrum, $\sim 20\,\mathrm{MeV}$ to $\sim 300\,\mathrm{GeV}$
- superior energy and angular resolution
- improve accuracy/energy range of EGRET by an order of magnitute
- 1st year LAT data released in August '09, more coming
- mid-latitude LAT data on diffuse γ-radiation $\Rightarrow$ little room for DM
- most interesting (and difficult): Galactic Center – still being analyzed

Galactic Center: excess in Fermi data?

Hooper et al. (several papers since 2009)

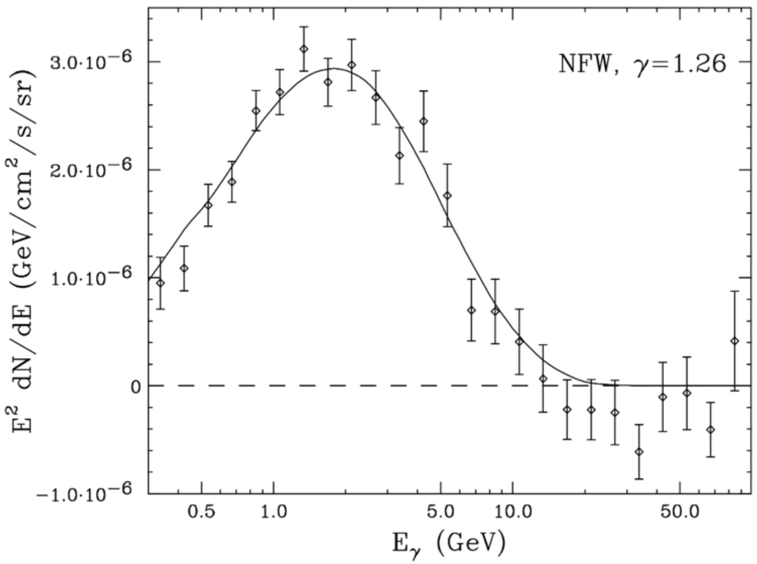
- **Excess distributed spherically around the GC, from an extended source (up to 10 deg)**

…reasonably convincing

Hooper et al. claim:

If this is due to DM then then flux:

- **falls off roughly as $r^{-2.4}$ (NFW, gamma=1.26)**
- **fits ``standard'' WIMP annihilation c.s. sigma*v of (1-2)x10^{-26} cm^3/s**
- **is consistent with WIMPs with mass 30-40 GeV annihilating to b-bbar**



With prompt gamma-ray emission only

However,

- **Taking into account diffuse gamma emission: better fit with WIMP mass of ~10 GeV and l-antil final state**
- **SMBH-induced DM spike would exceed Fermi data by ~10**

Lacroix, Boehm, Silk (1403.1987)

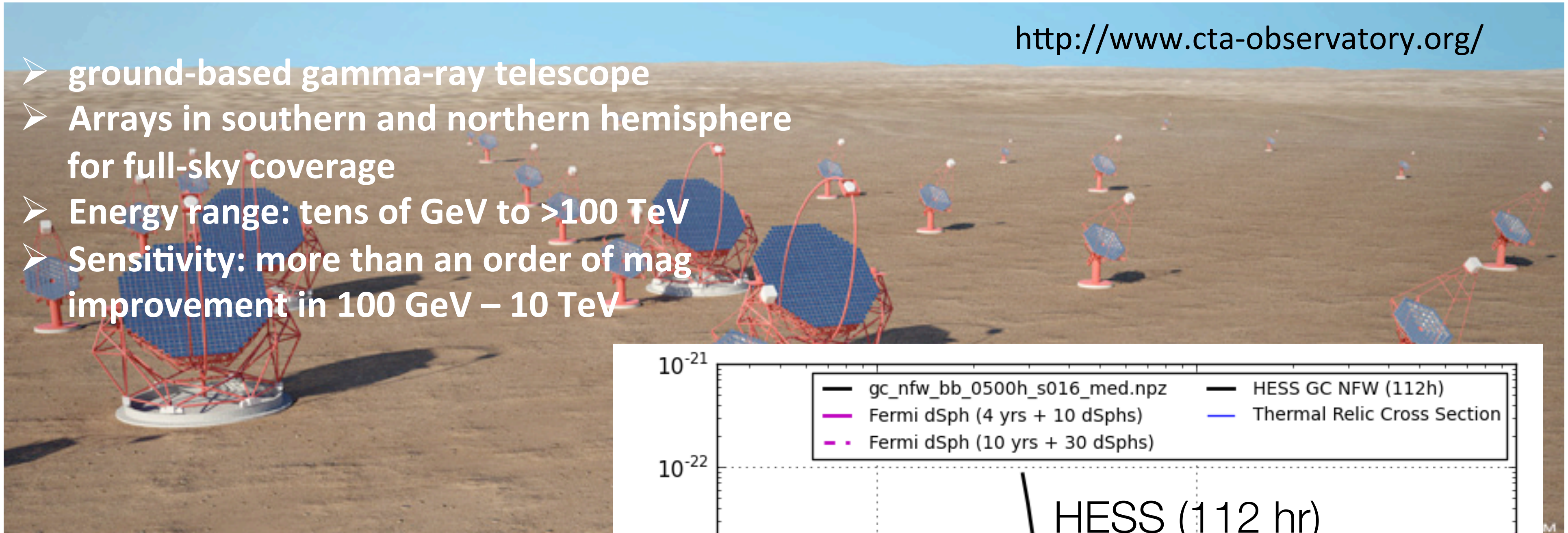
Fields, Shapiro, Shelton, 1406.4856

Crucially, astrophysical bgnd (and foreground) must be very well understood – and this is very tricky

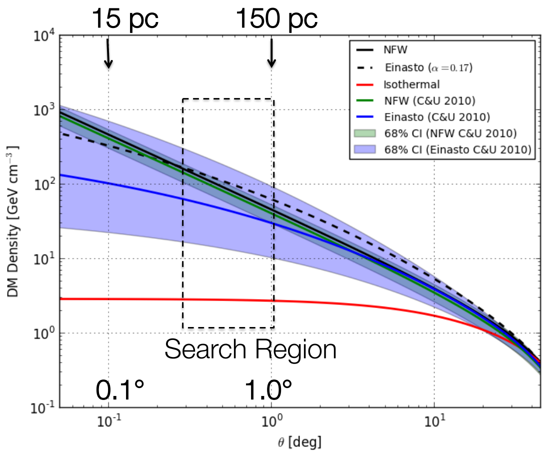
CTA – New guy in DM hunt race

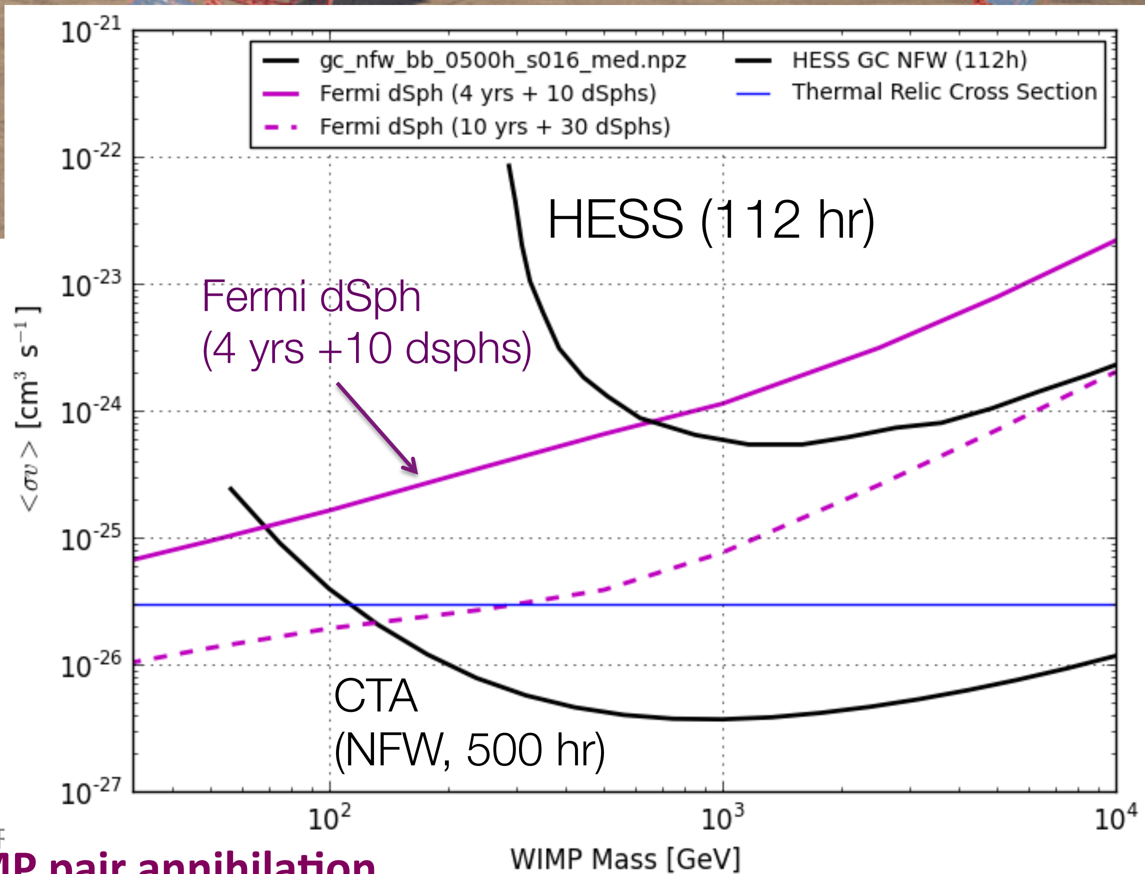
http://www.cta-observatory.org/

- ground-based gamma-ray telescope
- Arrays in southern and northern hemisphere for full-sky coverage
- Energy range: tens of GeV to >100 TeV
- Sensitivity: more than an order of mag improvement in 100 GeV – 10 TeV



Galactic Center DM Halo



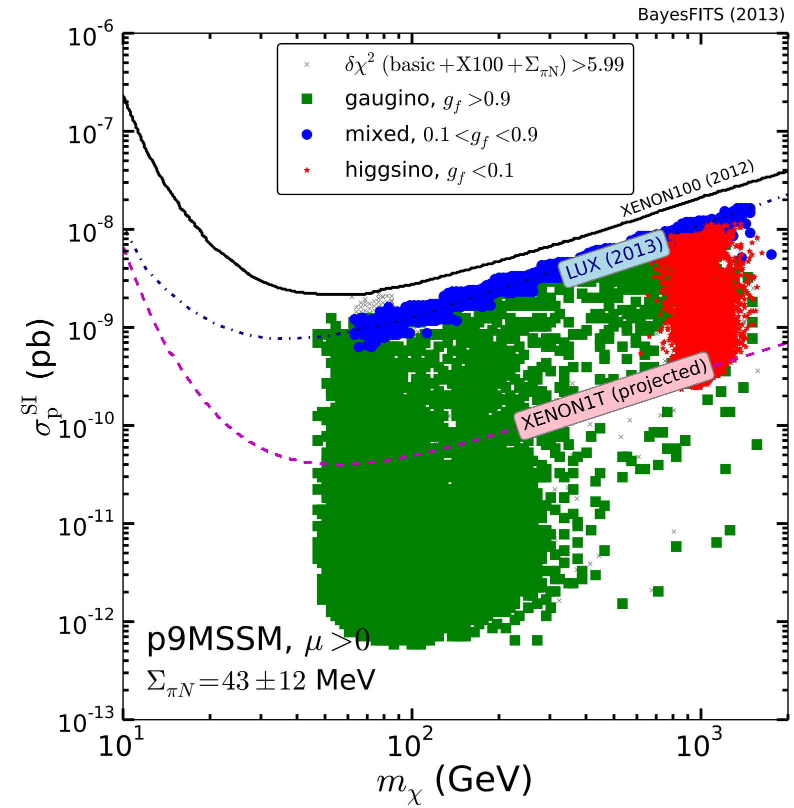


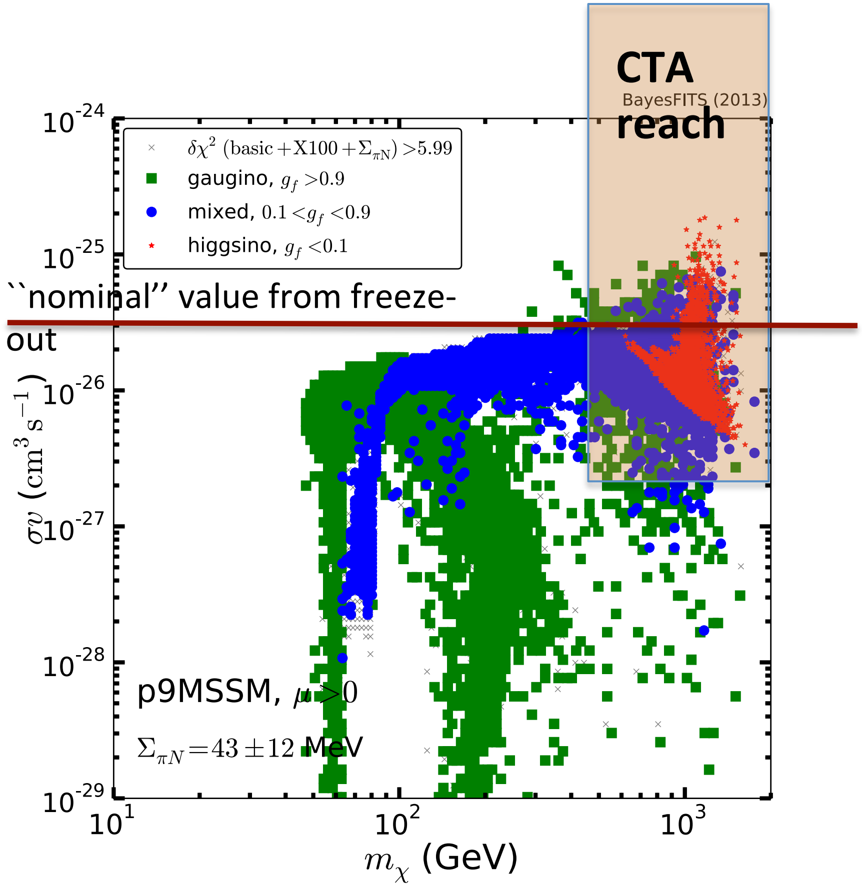
L. F

diffuse gamma radiation from WIMP pair annihilation

CTA and SUSY DM

Direct Detection





General SUSY (p9MSSM)

arXiv:1306.1567

MSSM:

- **CTA to probe large WIMP masses**
- **~1 TeV higgsino DM: to be completely covered by DD and CTA**

Gamma rays from DM annihilations

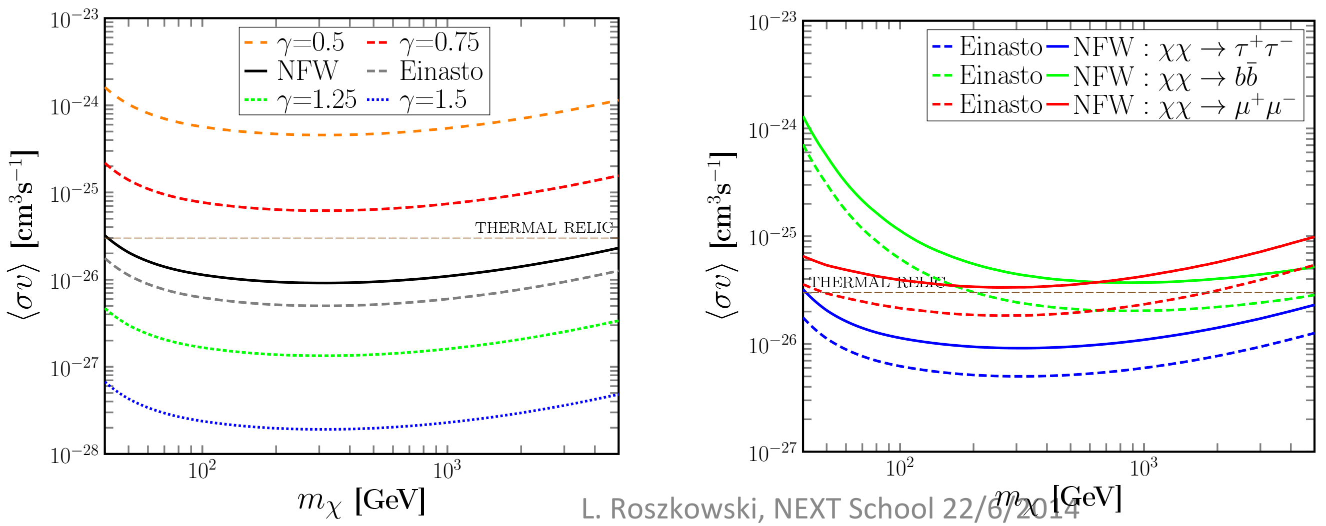
- WIMP pair-annihilation $\longrightarrow \boldsymbol{WW, ZZ, \bar{q}q}, \ldots \longrightarrow$ diffuse γ radiation (+ $\boldsymbol{\gamma\gamma}$, $\boldsymbol{\gamma Z}$ lines)
- diffuse γ radiation from direction ψ from the GC:

l.o.s - line of sight

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \psi) = \sum_i \frac{\sigma_i v}{8\pi m_\chi^2} \frac{dN_\gamma^i}{dE_\gamma} \int_{\rm l.o.s.} dl \rho_\chi^2(r(l,\psi))$$

- separate particle physics and astrophysics inputs; define:

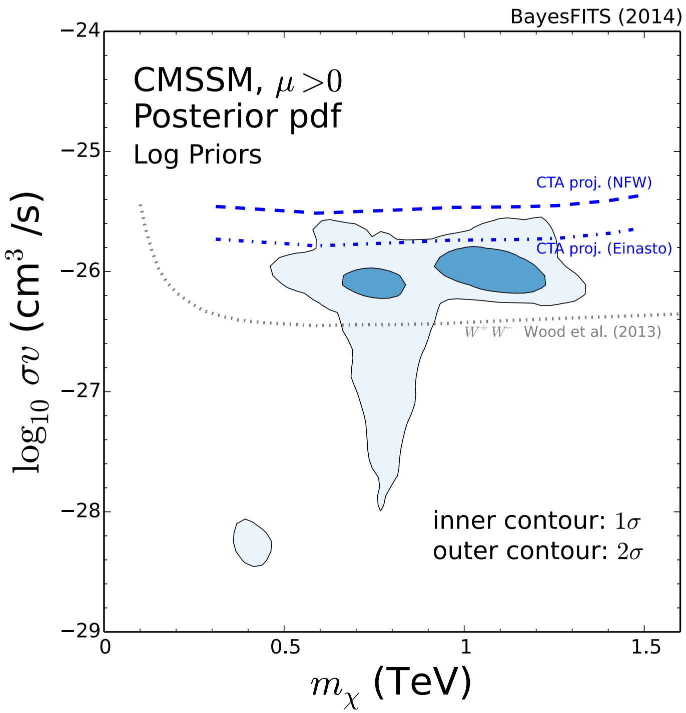
$$J(\psi) = \frac{1}{8.5\,\text{kpc}} \left(\frac{1}{0.3\,\text{GeV}/\,\text{cm}^3}\right)^2 \int_{\rm l.o.s.} dl\ \rho_\chi^2(r(l,\psi))$$

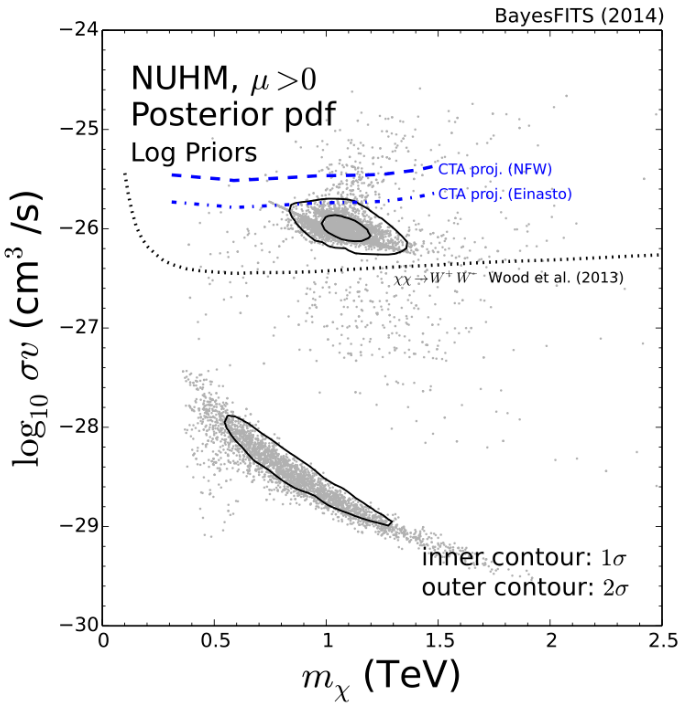


CTA reach

Pierre, Siegal-Gaskins, Scott, 1401.7330

CTA and Unified SUSY DM





1405.4289

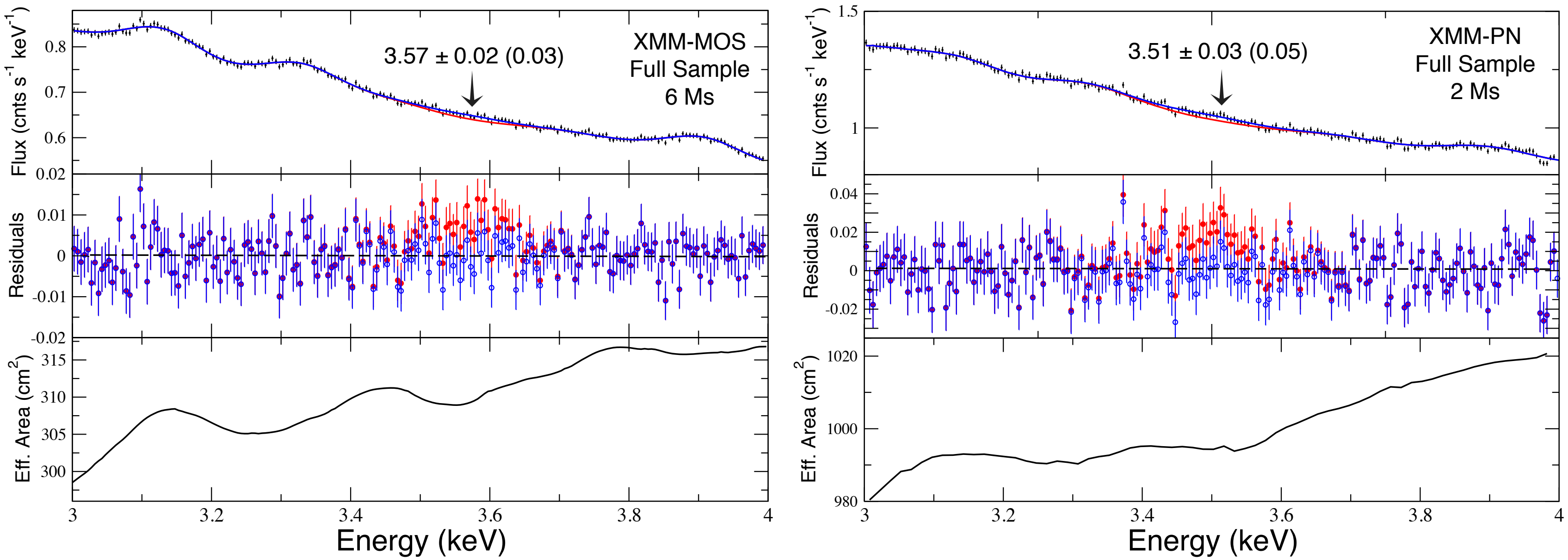
- **CTA to probe large WIMP masses**
- **~1 TeV higgsino DM: to be almost fully covered CTA**

X-Ray Signal of DM?

- **3.5 keV line is claimed to be seen in clusters of galaxies and in M31**

Bulbul, et al., 1402.2301
Boyarsky, et al., 1402.4119

(XMM data)



Combined data significance 4.4sigma

Lots of theoretical speculations:

- **Sterile neutrino decaying into an active one + photon**
- **Sterile nu -> axino**
- **Sterile nu -> axion-like particle**
- **…**

To take home:

- DM: evidence convincing but nature unknown
- jury is still out, discovery claims come and go

Low WIMP mass region probably gone

- Higgs of 126 GeV → ~1TeV (higgsino) DM – robust prediction of unified (and pheno) SUSY:

Smoking gun of SUSY!?

  - To be probed by 1-tonne DM detectors
  - Big bite by LUX already in 2014
  - Independent probe by CTA
  - Far beyond direct LHC reach

- DD: generally safest and most promissing way to find DM
- ID: often large, poorly understood astro bdg
  - Neutrinos, positrons: DM signal highly unlikely
  - Interesting excess at low energies in Fermi data
  - Wait and see with 3.5 keV X-ray line

Gazing into a crystal ball...

THE SUNDAY TIMES · SEPTEMBER 21, 2003

There's a black hole in the middle of our finances


CREDIT
CRUNCH
AHEAD

Gazing into a crystal ball...

SUSY may be too heavy for the LHC

DM searches may hopefully come to the rescue


We need a genuine
WIMP signal…
… from more than one
DM search experiment